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DESIGN OF A LATERAL STABILITY AUGMENTATION SYSTEM
FOR THE F-106 TO IMRPOVE LATERAL HANDLING QUALITIES
DURING TRACKING

Richard D. Holdridge, Captain, USAF

Flight Control ADP Branch
Flight Control Division

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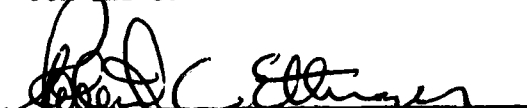Approved for public release; distribution unlimited·

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An improved lateral stability augmentation system has been developed to improve the handling qualities of the F-106 in the air-to-air tracking task. The existing yaw rate and roll rate feedbacks, as well as the aileron to rudder interconnect, were removed and replaced with calculated sideslip rate and measured sideslip feedbacks. An advanced root locus technique, the root map was used to set the gains on sideslip and sideslip rate. The resulting system was evaluated using a nonpiloted hybrid simulation as well as a digital

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20. ABSTRACT (Concluded)

frequency domain analysis program. The system was then evaluated by
operational F-106 pilots using the Flight Dynamics Laboratory's LAMARS
motion based simulator. Based on simulator results, the system was
installed on an F-106 and flight tested at Tyndall AFB, Florida. The
results of basic analyses, nonpiloted simulations, piloted simulations,
and flight test are presented.

FOREWORD

This report documents an effort to use conventional design methods in the design of an improved stability augmentation system for the F-106.

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LIST OF SYMBOLS

$A_y)_{acc}$ Accelerometer measured lateral acceleration (ft/sec^2)

b   Wingspan (ft)

$\bar{c}$ Mean aerodynamic chord (ft)

C_D Non-dimensional drag coefficient

C_L Non-dimensional lift coefficient

C_l Non-dimensional rolling moment coefficient

C_m Non-dimensional pitching moment coefficient

C_n Non-dimensional yawing moment coefficient

C_y Non-dimensional sideforce coefficient

F_x Total force in body x-direction (lb)

F_y Total force in body y-direction (lb)

F_z Total force in body z-direction (lb)

g   Gravitational acceleration, 32.174 ft/sec^2

I_x Moment of inertia about body x-axis (slug ft^2)

I_y Moment of inertia about body y-axis (slug ft^2)

I_z Moment of inertia about body z-axis (slug ft^2)

I_{xz} Moment of inertia xz cross-product (slug ft^2)

K   Transfer function gain for $\beta/\delta r$

K_I Gain on integrator in proportional plus integral compensator

K_p Gain from rudder pedals to control system (rad/in)

K_β Gain on sideslip angle feedback (rad/rad)

$K_{\dot{\beta}}$ Gain on sideslip angle rate feedback (rad/rad/sec)

L   Total rolling moment (ft-lb)

M   Total pitching moment (ft-lb)

M   Mach number

m   Mass (slugs)

N	Total yawing moment (ft-lb)
n.p.	Neutral Point (ft)
p	Roll rate (rad/sec)
q	Pitch rate (rad/sec)
$\bar{q}$	Dynamic pressure (lb/ft^2)
r	Yaw rate (rad/sec)
S	Wing area (ft^2)
u	Velocity in body x-direction (ft/sec)
U	Total velocity (ft/sec)
v	Velocity in body y-direction (ft/sec)
$\bar{v}_b$	Body velocity vector (ft/sec)
$\dot{\bar{v}}_b$	Body acceleration vector (ft/sec^2)
$\dot{\bar{v}}_b$	Inertial acceleration vector (ft/sec^2)
w	Velocity in body z-direction (ft/sec)
$x_{c.g.}$	Center of Gravity (ft)
α	Angle of attack (rad)
β	Sideslip angle (rad)
$\dot{\beta}_a$	Sideslip angle rate (rad/sec)
δ'_a	Aileron deflection (rad)
δ_e	Elevator deflector (rad)
δ_r	Rudder deflection (rad)
ϕ	Roll angle (rad)
θ	Pitch angle (rad)
$\bar{\omega}$	Body angular rate vector (rad/sec)

SECTION I

INTRODUCTION

An improved lateral stability augmentation system (SAS) for the F-106 has been designed and simulated in both piloted and non-piloted real-time simulations and in a frequency domain simulation. The new system emphasizes improvement in lateral handling qualities for the air-to-air (ATA) tracking task.

The present lateral SAS is composed of washed out yaw rate, for stability purposes, and a combination of washed out roll rate and an aileron to rudder interconnect (ARI), for turn coordination. The new system uses sideslip angle (β) and sideslip angle rate ($\dot{\beta}$) to achieve both improved stability and improved turn coordination. The design also includes a direct electrical signal from the pilot through the rudder pedals to the control system to allow for direct command of sideslip angle or sideslip rate.

The new system eliminates large unintentional sideslip perturbations caused by the pilot's attempts to place the gunsight reticle, or pipper, on the target aircraft. The system also allows the pilot to point more accurately the aircraft when azimuth tracking error is small. An added benefit provided by the system is an improvement in elevation tracking error through a reduction of pilot workload in the lateral task.

A piloted simulation was conducted to evaluate the new lateral SAS. Two Air Defense Command (ADCOM) flight test pilots, both current in the F-106, spent a week flying approximately 150 ATA tracking passes. Several configurations of the improved system were flown and compared with the existing system. The pilots typically achieved reductions of 30% in both elevation and azimuth tracking error using the improved lateral SAS. The system was then installed on an F-106 and flight tested. The performance improvements were similar to those measured during piloted simulations.

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SECTION II

BACKGROUND

1. AIR-TO-AIR TRACKING

Before continuing with a specific discussion of the F-106, it is perhaps instructive to look at the ATA tracking task and how the difficulty of the task is heavily influenced by the aircraft flight control system. ATA tracking is typically a high-g maneuver which has superimposed on it the extremely difficult task of precise aircraft pointing. The task is further complicated because the aircraft is not being pointed as an end in itself but to enable the pilot to place a gunsight reticle (pipper), either fixed or computed and displayed, on the target aircraft. Since the pipper is a representation of a target for which the gun is presently correctly aimed, it will be depressed some angle from the aircraft body x-axis. This depression is due to target aircraft acceleration, attacker velocity and acceleration, and bullet gravity drop; its magnitude is further dependent on the angle of the gun with respect to the aircraft (gun depression angle). Figure 1 shows this situation and how it is viewed by the pilot in the headup display (HUD). Figure 1 also shows how elevation tracking error is defined. The tracking error is usually measured in angular units of milliradians (mil). In the situation shown in Figure 1, the pilot's task is simple: he pitches the aircraft up until the reticle is superimposed on the target.

Unfortunately, when a large azimuth error also exists, the pilot cannot simply move the reticle onto the target. To zero a large azimuth tracking error, the pilot must first roll the aircraft to approximately null the azimuth error and then pitch the aircraft to null the remaining elevation error. After these large azimuch errors have been nulled, the rudder pedals can be used to zero the remaining error. This sequence of first nulling azimuth error then elevation error is the basis upon which each pilot developes his own technique.
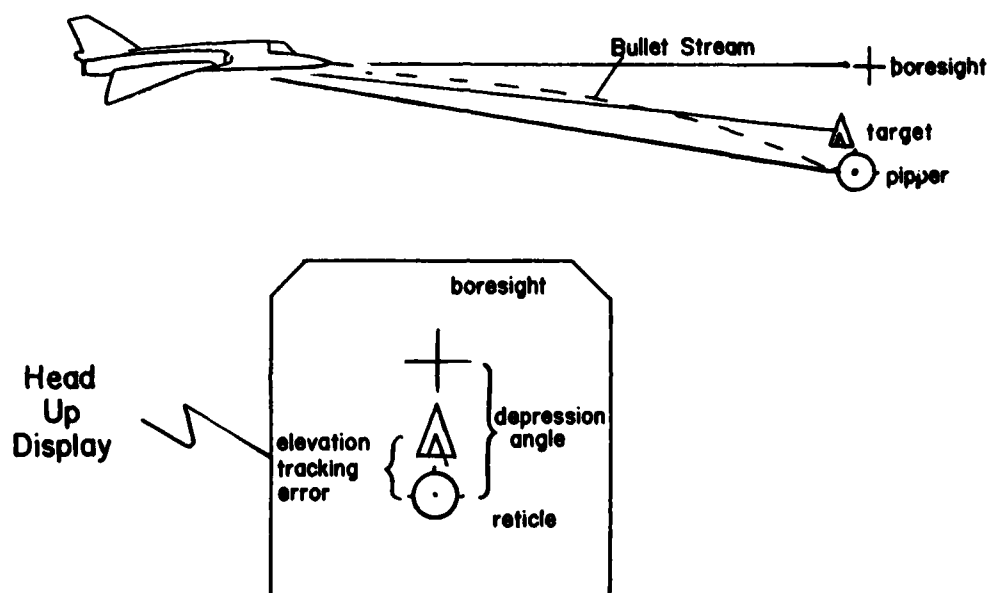
Figure 1. Reticle Depression Angle and Tracking Error

2. FACTORS AFFECTING ATA TRACKING

There are many factors which affect the pilot's ability to track a target. Some of these factors are turbulence, evasive target maneuvers, gunsight dynamics, and the attacker's own vehicle dynamics. The first two are factors that cannot be controlled or changed by modifications to the attacking aircraft. The third term can have a significant effect on tracking performance and to a large extent can be controlled or changed by modifications to the fire control system of the attacking aircraft. The study of gunsight dynamics and other associated fire control problems is, however, beyond the scope of this paper. To simplify the effects of gunsight dynamics, a fixed depressed reticle was used for the remainder of this study. A fixed depressed reticle, as the name implies, is a gunsight reticle which is depressed a constant angle from the boresight cross. Figure 2 shows a simple fixed depressed reticle as seen on the HUD. The fourth factor affecting the pilot's ability to track the target is vehicle dynamics. Like gunsight dynamics, vehicle dynamics can be changed by modifications to the attacking aircraft.
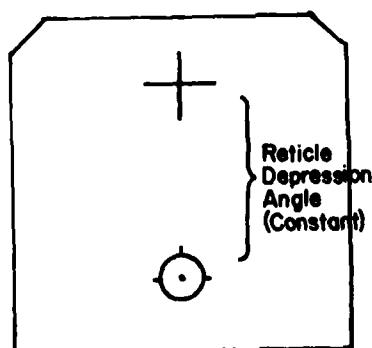
Figure 2. Fixed Depressed Reticle

To see how the vehicle dynamics affect the tracking error, one must compare what the pilot sees through the HUD to what the aircraft is doing within the airmass. Consider the HUD display in Figure 3(a) with a fixed depressed reticle. Since the pipper is left of the target, the pilot must null the azimuth error. Since the pilot cannot move his aircraft laterally, he must first roll the aircraft right and then turn to zero the error. Herein lies the problem. If the aircraft is unaugmented or contains just simple yaw damping, the aileron deflection will cause the aircraft to rotate about its nearest principle axis. For a rolling moment, this principle axis is very near the x-axis of the aircraft or, from the pilot's point of view, the boresight axis. This roll/sideslip coupling is shown in Figure 4. What then happens from the pilot's viewpoint is shown in Figure 3(b). When he rolls the aircraft, he rolls approximately about the boresight cross thus generating a transient sideslip angle which causes the pipper to move in the direction opposite that desired by the pilot. The pilot perceives this as an increased azimuth error, so he rolls the aircraft more to the right (Figure 3(c)), compounding the problem. This phenomenon of the pipper rotating under the boresight cross is known as the pendulum effect and has a destabilizing effect on ATA tracking.

The pendulum effect can be eliminated or greatly reduced by lateral augmentation of the aircraft. Figures 3 and 4 show that the pendulum effect is caused by the aircraft's natural trndency to roll about its own x-axis. This results in the angle-of-attack changing into sideslip as the roll angle goes from 0 to 90 degrees. Of course, this sideslip will die out at the aircraft's dutch roll frequency and damping, but this is too slow for the tracking task.

Another aspect of aircraft dynamics that affects the pilot's ability to track becomes obvious only when large tracking errors have been eliminated and the pilot is using the rudder to point the aircraft. When the pilot is using the rudder for fine control of azimuth error, the dutch roll frequency and damping become critical to the tracking task. To be effective during this precise phase of tracking, the aircraft should respond quickly to the pilot's input with a damping ratio which eliminates large overshoots and at the same time avoids the excessive lag of an

a. Initial Condition

b. Pilot rolls right

c. Pilot rolls further right
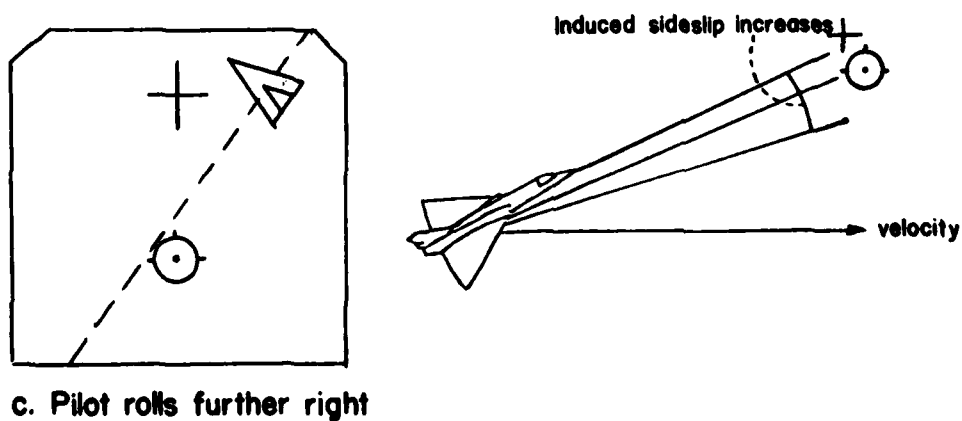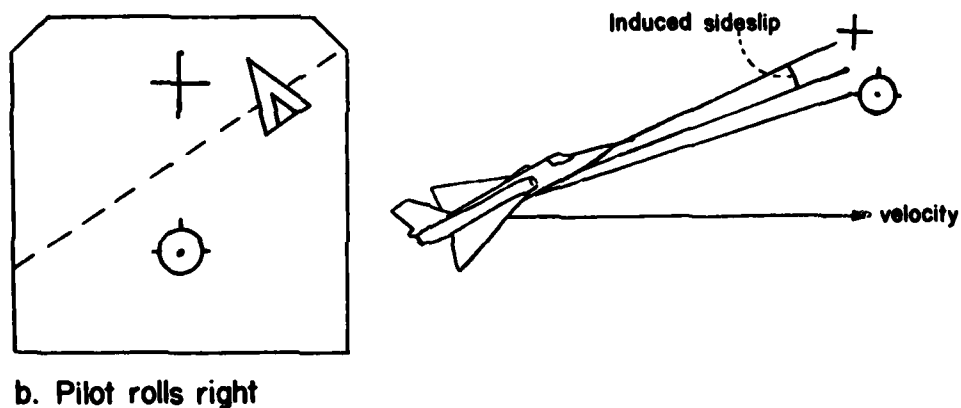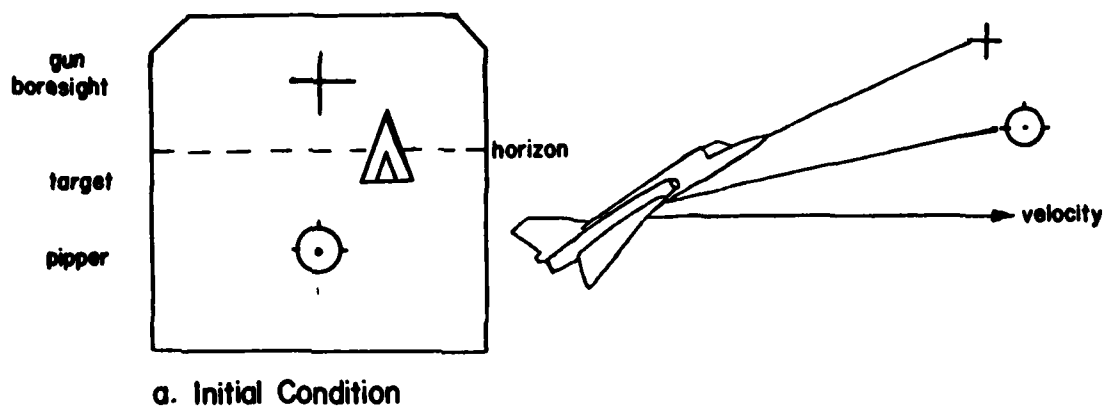
Figure 3. The Pendulum Effect

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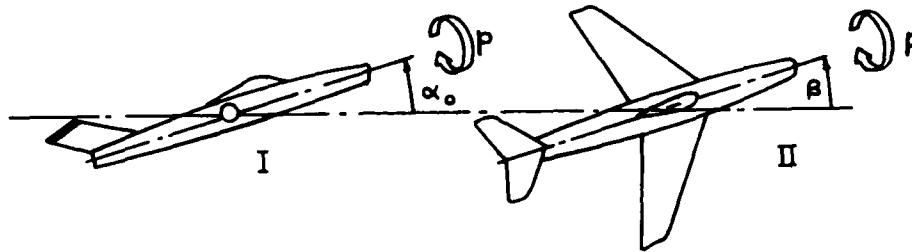
Figure 4. Roll/Sideslip Coupling

overdamped response. An overdamped response could result in the airplane becoming too sluggish as perceived by the pilot. Typically a dutch roll damping ratio of .7 to 1 is adequate. In this precise lateral pointing, the pilot desires to yaw the aircraft without significant roll coupling.

3. CONTROL SYSTEMS FOR AIR-TO-AIR TRACKING

After seeing how an unaugmented aircraft behaves when used to track a target, the possibilities of improvement using augmentation are obviously significant. The answer is found by looking again at Figures 3 and 4. If the aircraft were to roll about the velocity vector instead of the x-axis, the pendulum effect could be eliminated or greatly reduced. Figure 5 shows the same initial conditions as Figure 3 but shows how the pilot's task would be simplified if the aircraft was forced to roll about the velocity vector.

The design of a control system to improve aircraft dynamics for ATA tracking is based on this capability of rolling about the velocity vector. The result of rolling about the x-axis in the case of an unaugmented aircraft, is the increase of sideslip and reduction of angle of attack. This induced sideslip is the basis for the design of the control system. If the sideslip angle is kept at zero during the roll, then the aircraft is rolling about the velocity vector. The desired control system is therefore an accurate and responsive turn coordinator. The feedbacks needed to achieve this turn coordination are sideslip angle and sideslip

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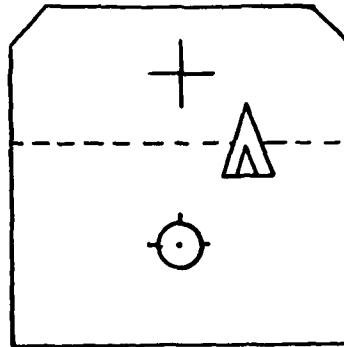
a. Initial Condition
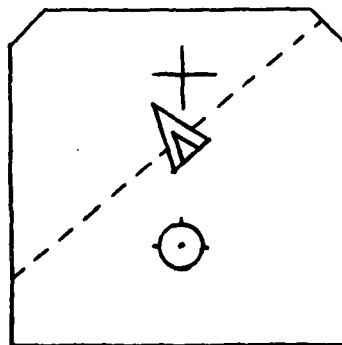
b. Roll Right to Zero Azimuth Error
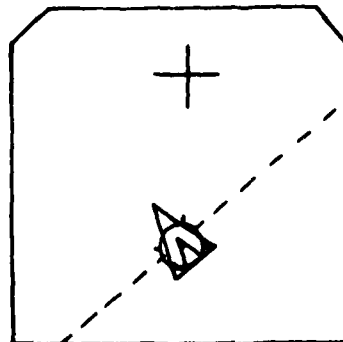
c. Pitch Up to Null Final Elevation Error

Figure 5.   Rolling about Velocity Vector

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angle rate. A simplified block diagram of this control system is shown in Figure 6. Since sideslip angle and sideslip rate are also the aircraft states which can be controlled by the pilot with the rudder pedals, this control system will also affect the aircraft response to rudder pedal input. This means that the pilot's task of fine lateral pointing can be improved using the system of Figure 6.

4. F-106 DYNAMICS

A hybrid simulation of the F-106 was conducted on the Aeronautcial Systems Division Hybrid Computer to study the F-106 in a real-time situation. The simulation was validated by checking angle of attack and elevator deflection at numerous flight conditions throughout the F-106 flight envelope. Dynamic longitudinal and lateral checks were also made at various flight conditions. The model used in the simulation proved to be an accurate representation of the real aircraft. A description of the simulation is included in Appendix A.

The purpose of the hybrid simulation was to look at the aircraft with the present control system and determine if it did demonstrate character-istics detrimental to ATA tracking. The two characteristics most likely to be encountered were the roll/sideslip coupling and the underdamped dutch roll. The standard SAS is shown in Figures 7a and 7b. The yaw rate feedback is present primarily to achieve the needed dutch roll damping. The roll rate feedback and ARI exist primarily to achieve turn coordination or, equivalently, to allow the aircraft to roll approximately about the velocity vactor.

The responses of the bare airframe (SAS turned off) to a 60-degree roll input are shown in Figure 8. The roll angles were input using a roll autopilot with a 1-second time constant. These responses show sideslip perturbations of more than 1 degree with very low damping, on the order of .15. Both characteristics would indicate the F-106 with the SAS turned off could have deficient lateral handling qualities during ATA tracking. The 60-degree roll angle command was also input to the F-106 at the same flight conditions but with the standard SAS turned on. The results, shown in Figure 9, are significantly better than the bare airframe.

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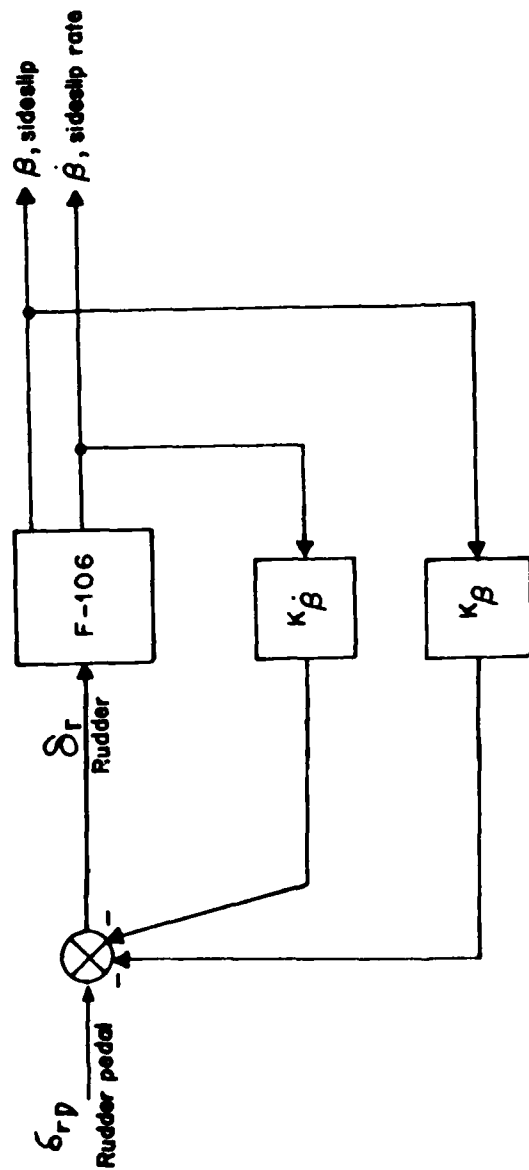
Figure 6.   Sideslip Control System
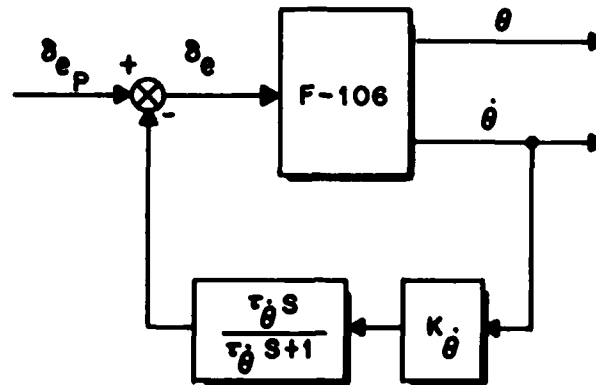
SCHEDULED GAIN AND TIME CONSTANTS
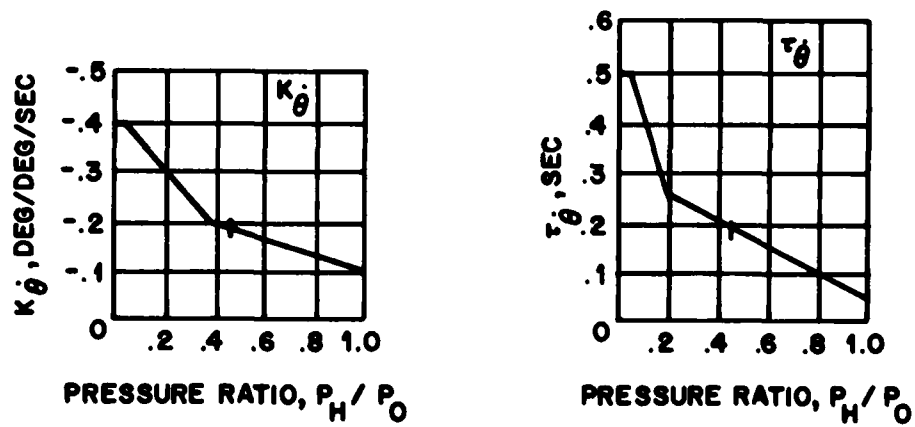
Figure 7a.   F-106 Longitudinal SAS

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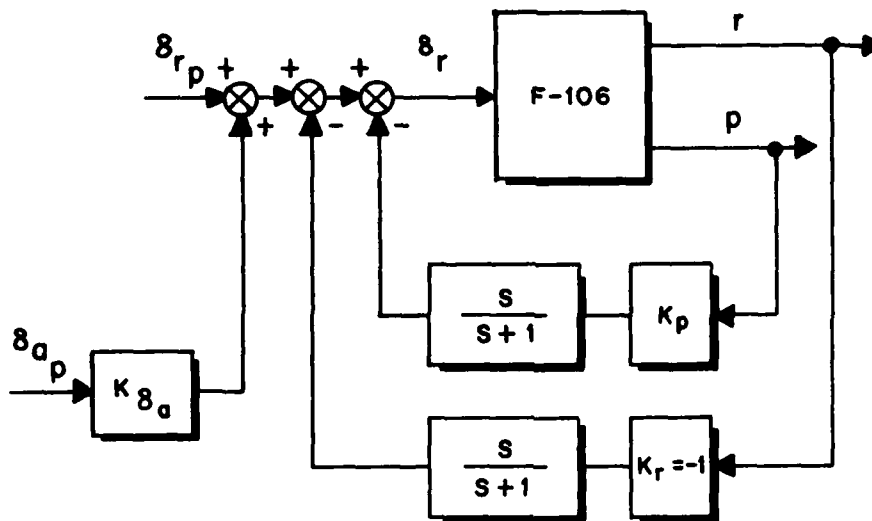
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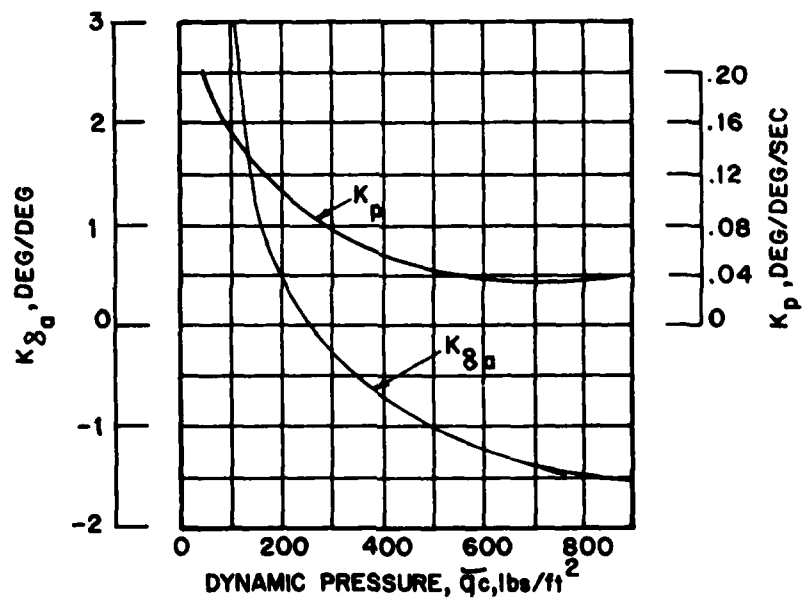
Figure 7b.   F-106 Lateral SAS

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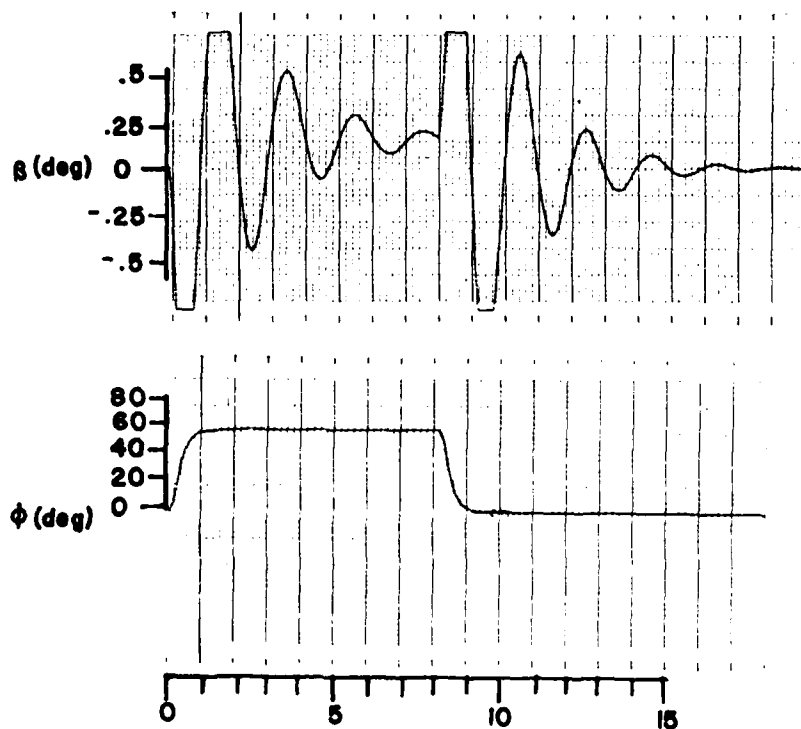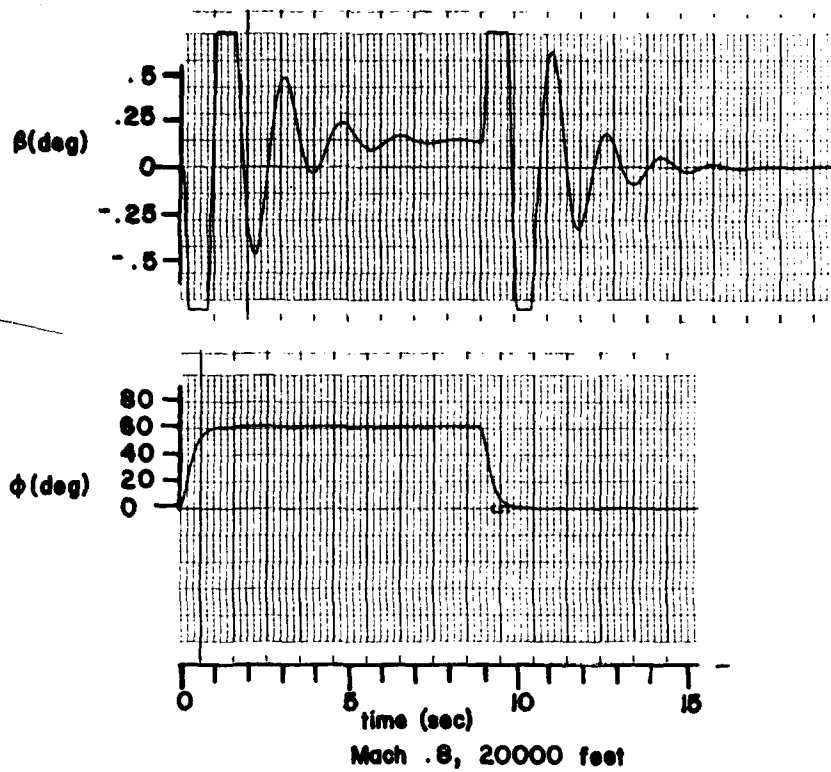
Figure 8.   Bare Airframe Response to 60° Band Angle

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The damping increases markedly from about .1 to .7. Although the standard SAS improves the underdamped dutch roll characteristic, the large sideslip perturbation, as seen in the bare airframe responses, is also present in the standard SAS. This roll/sideslip coupling indicates a factor which will affect the lateral tracking characteristics of the aircraft.

This preliminary analysis of the F-106 indicates possible areas of improvement in the lateral handling qualities. The bare airframe is obviously undesirable in terms of both dutch roll damping and roll/sideslip coupling. The standard SAS improves dutch roll damping considerably but the roll/sideslip perturbations are still large. Figures 8 and 9 show the dynamic responses for the standard SAS due to roll angle inputs from straight and level, 1 g flight. At higher g loadings, typical for air-to-air tracking, the induced sideslip angle would be larger than those shown in Figures 8 and 9. Based on these significant sideslip perturbations, it therefore seemed appropriate to consider a sideslip angle/sideslip angle rate (β-$\dot{\beta}$) control system, as mentioned earlier, for use on the F-106.
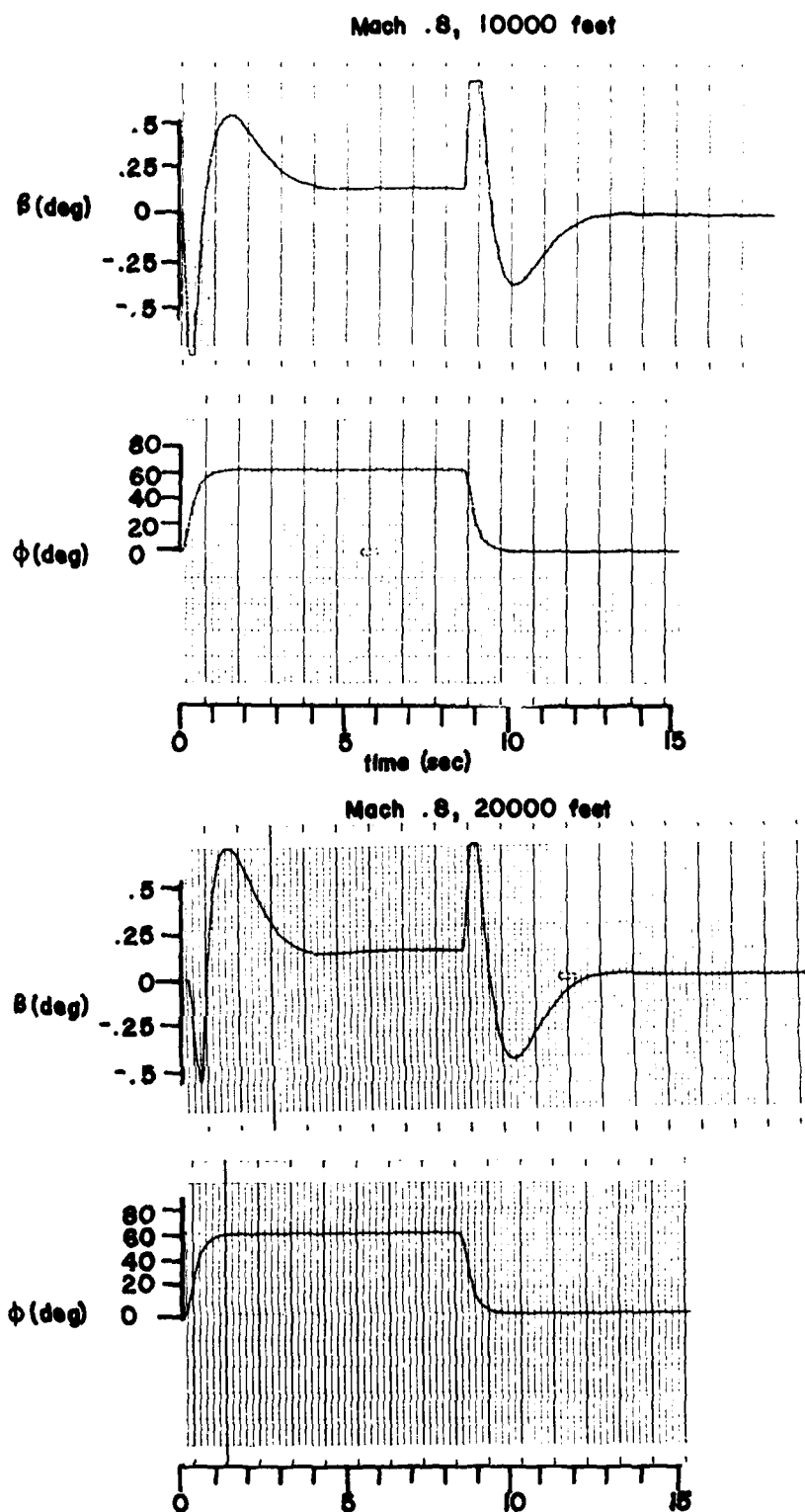
Figure 9.   Standard SAS Response to 60° Bank Angle

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SECTION III

SYSTEM DESCRIPTION

1. PRELIMINARY DESIGN MODEL

The system shown in Figure 10 is the basis for a preliminary design of a β-$\dot{\beta}$ SAS for the F-106. By design, the system will tend to cause the aircraft to maintain coordinated flight or, equivalently, to roll about the velocity vector; therefore, the task remaining in the preliminary design is to find the gains K_β and $K_{\dot{\beta}}$ to provide sufficient damping and adequate speed of response. The proportional plus integral compensator is included to remove the steady-state error resulting from the β feedback. The integral gain K_I is nominally set to .2 for the analysis.

2. ROOT MAP ANALYSIS

The closed-loop dynamic characteristics of the system are analyzed using the root map technique (Reference 3). This technique involves closing one loop at a constant gain, either sideslip or sideslip rate, then plotting the root locus by allowing the other gain to vary from zero to infinity. For generating a root locus at a constant K_β, the system model appears as Figure 11. The simplified transfer function, $\beta/\delta r$, is based on McRuer's (Reference 7) fourth order model and is shown below.

$$\beta/\delta r = \frac{K(s + a)}{s^2 + bs + c}$$

$$K = Y^*_{\delta r} \qquad\qquad b = -(Y_v + N'_r)$$

$$a = -(Y^*_{\delta r}N'_r + N'_{\delta r})/Y^*_{\delta r} \qquad\qquad c = (N'_\beta + Y_v N'_r) \tag{1}$$

The dimensional aerodynamic derivatives making up the transfer function are described in Reference 7 and the resulting transfer functions are displayed in Appendix B.
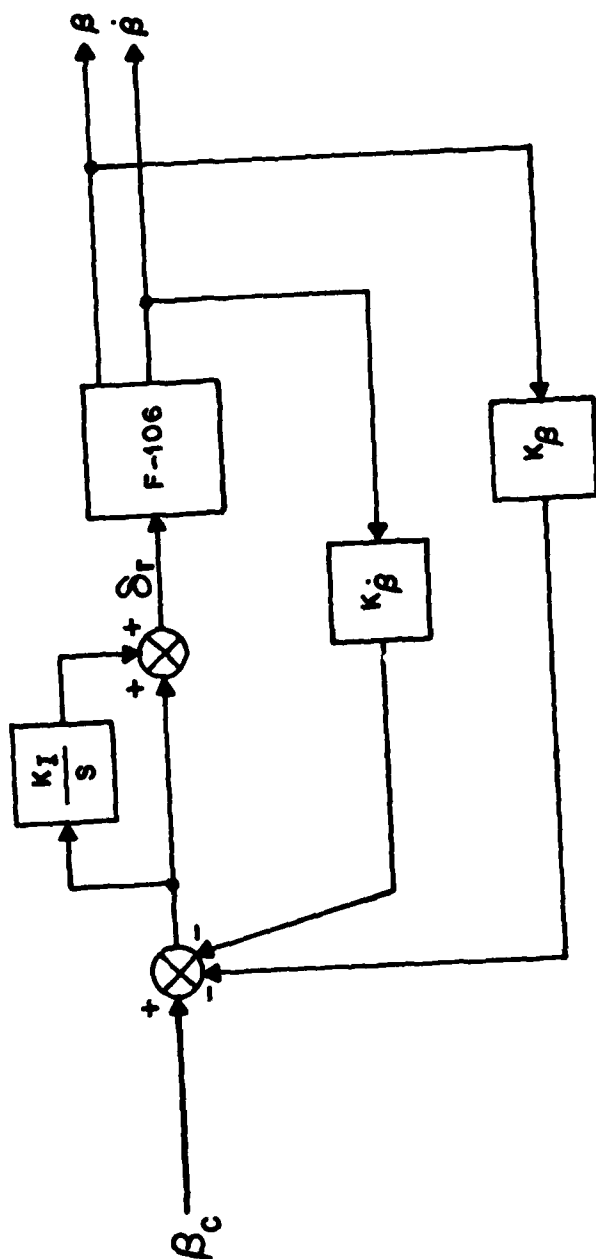
Figure 10.   Preliminary Design Model
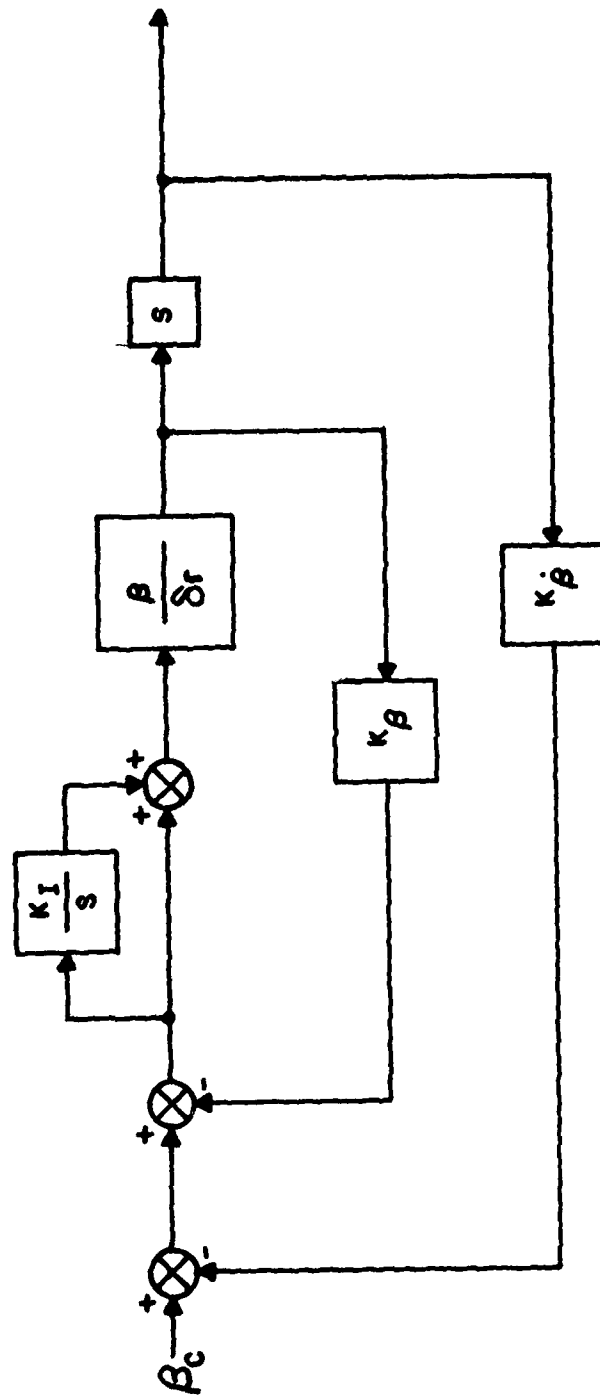
Figure 11. System Model for Constant K_β

To generate a root locus for a varying $K_{\dot{\beta}}$, the beta inner loop must first be closed at a given value of K_β and the inner loop transfer function calculated.

$$\frac{G}{1 + GH}\Big|_{\substack{\text{Inner Loop} \\ \text{const } K_\beta}} = \frac{\dfrac{K(s + a)(s + K_I)}{s(s^2 + bs + c)}}{1 + \dfrac{K_\beta K(s + a)(s + K_I)}{s(s^2 + bs + c)}} \tag{2}$$

Simplifying.

$$\frac{G}{1 + GH}\Big|_{\substack{\text{Inner Loop} \\ \text{const } K_\beta}} =$$

$$\frac{K(s + a)(s + K_I)}{s^3 + (b + KK_\beta)s^2 + [c + KK_\beta(K_I + a)]s + KK_I K_\beta a} \tag{3}$$

The open loop transfer function for the complete system is now obtained by multiplying the inner loop transfer function, Equation 3, by $sK_{\dot{\beta}}$

$$GH)\Big|_{\substack{\text{Overall} \\ \text{Const } K_\beta}} = \frac{K_{\dot{\beta}} Ks(s + a)(s + K_I)}{s^3 + (b + KK_\beta)s^2 + [c + KK_\beta(K_I + a)]s + KK_I K_\beta a} \tag{4}$$

Using Equation 4, root locus plots are drawn for different values of K_β. These plots show the closed loop poles for a given value of K_β as $K_{\dot{\beta}}$ varies from zero to infinity. Unfortunately, the gain $K_{\dot{\beta}}$ is not explicit on the root locus. The desired closed-loop pole location must be chosen and then compared with the tabular output to find the corresponding value of $K_{\dot{\beta}}$. This is an extremely time consuming process when responses at given values

of K_β and $K_{\dot\beta}$ must be compared throughout the flight envelope. To simplify this process of gain selection, root loci were also drawn at constant values of $K_{\dot\beta}$.

A procedure similar to the method described above is used to get these root locus plots at constant values of $K_{\dot\beta}$. Figure 12 shows the system model used for this procedure. The transfer function $\dot\beta/\delta r$ is just $s\beta/\delta r$, as shown below, where $\beta/\delta r$ is the same as Equation 1.

$$\dot\beta/\delta r = \frac{Ks(s + a)}{s^2 + bs + c} \qquad (5)$$

Using Figure 12, the betadot inner loop is closed first to obtain the inner-loop transfer function.

$$\left.\frac{G}{1 + GH}\right|_{\substack{\text{Inner Loop} \\ \text{Const } K_{\dot\beta}}} = \frac{\dfrac{Ks(s + a)(s + K_I)}{s(s^2 + bs + c)}}{1 + \dfrac{K_{\dot\beta}K(s + a)(s + K_I)s}{s(s^2 + bs + c)}} \qquad (6)$$

Simplifying.

$$\left.\frac{G}{1 + GH}\right|_{\substack{\text{Inner Loop} \\ \text{Const } K_{\dot\beta}}} =$$

$$\frac{\dfrac{K}{1 + K_{\dot\beta}K}s(s + a)(s + K_I)}{s^3 + \dfrac{b + K_{\dot\beta}K(K_I + a)}{1 + K_{\dot\beta}K}s^2 + \dfrac{c + K_{\dot\beta}K_I Ka}{1 + K_{\dot\beta}K}s} \qquad (7)$$

The open-loop transfer function for the complete system is obtained by multiplying the inner loop transfer function, Equation 7, by K_β/s.
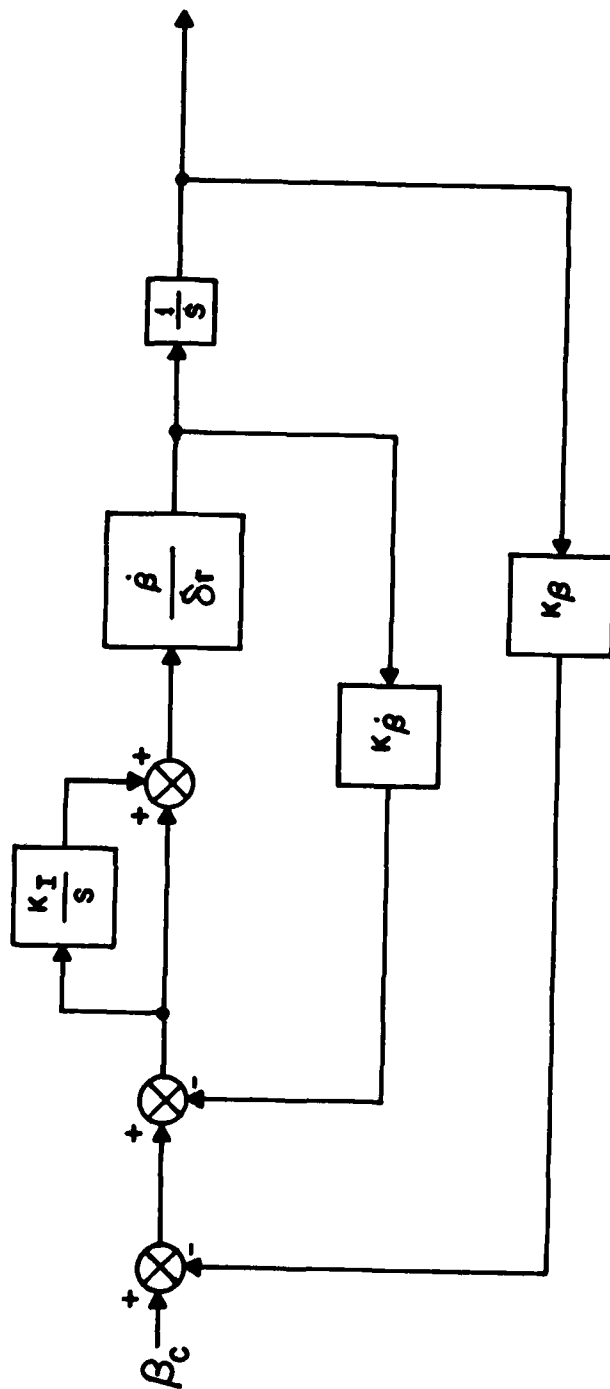
Figure 12. System Model for Constant K_β^*

$$(GH)_{\substack{\text{Overall} \\ \text{Const } K_{\dot{\beta}}}} = \frac{\dfrac{K_{\beta}K}{1 + K_{\dot{\beta}}K}(s + a)(s + K_I)}{s^3 + \dfrac{b + K_{\dot{\beta}}K(K_I + a)}{1 + K_{\dot{\beta}}K}s^2 + \dfrac{c + K_{\dot{\beta}}K_I Ka}{1 + K_{\dot{\beta}}K}s} \tag{8}$$

Using Equation 8, root locus plots for different values of $K_{\dot{\beta}}$ can be drawn. Poles and zeros of Equations 4 and 8 are tabulated in Appendix B for the flight condition analyzed.

To construct a root map, root loci are calculated, using Equations 4 and 8. Constant K_{β} root locus plots are drawn by setting K_{β} constant in Equation 4 and letting $K_{\dot{\beta}}$ varying from zero to infinity. Values of K_{β} from 1 to 15 are used. The constant $K_{\dot{\beta}}$ root locus plots are drawn in the same manner except that $K_{\dot{\beta}}$ is fixed and K_{β} varies. Values of $K_{\dot{\beta}}$ from 1 to 7 are used. The root map consists of these 22 root locus plots displayed on the same s-plane.

Root maps were constructed for the flight conditions shown in Table 1 to insure that the gains chosen for K_{β} and $K_{\dot{\beta}}$ are adequate for the entire flight envelope. Figures 13a through 13i show these root maps. Also displayed on the maps is the boundary for a good response, a response acceptable for ATA tracking. The boundary represents specifications of the damping ratio from .65 to .75 and the natural frequency from 3.5 to 6 rad/sec. The specified damping ratio would provide good lateral damping while the specified natural frequency provides adequate speed of response.

TABLE 1

ROOT MAP FLIGHT CONDITIONS

Map	Mach	Altitude
1	.4	S.L.
2	.9	S.L.
3	.7	10000
4	.6	15000
5	.9	15000
6	1.2	15000
7	.6	30000
8	.9	30000
9	1.4	30000

+ = operating point
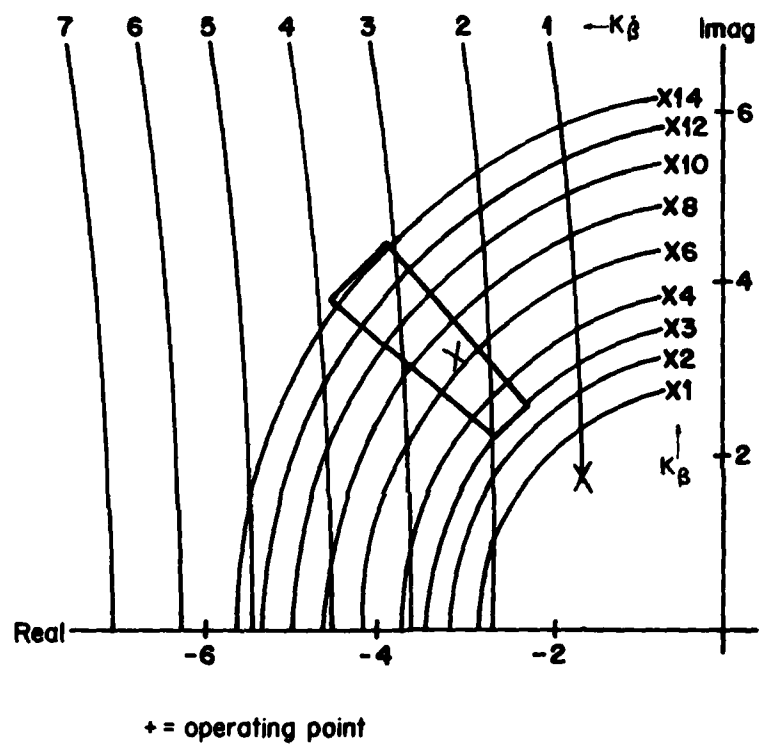
Figure 13a.   Root Map at Mach .4, Sea Level

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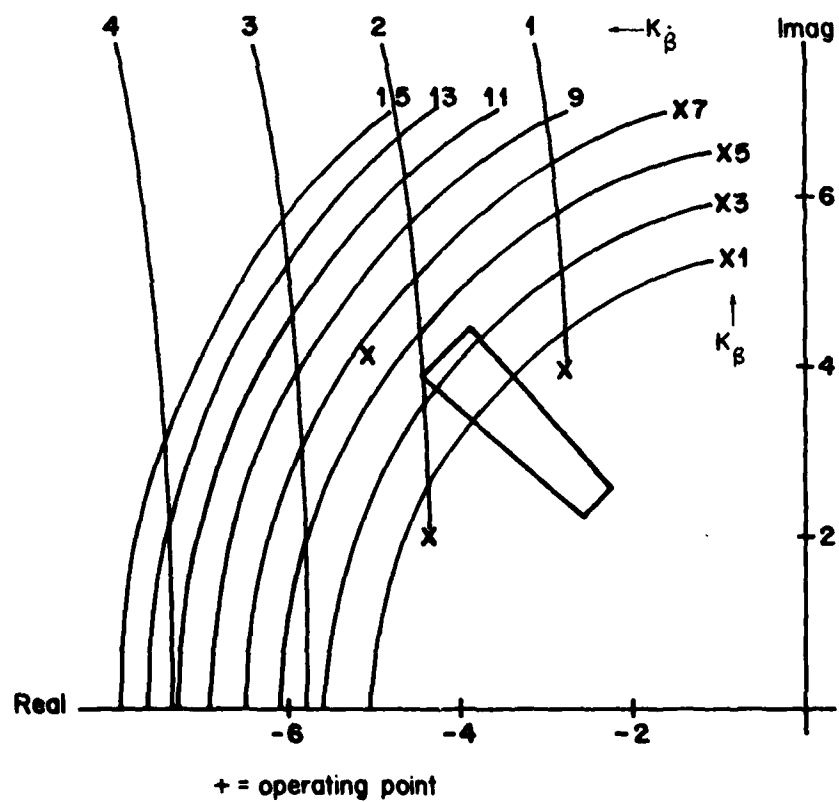
Figure 13b.   Root Map at Mach .9, Sea Level

24
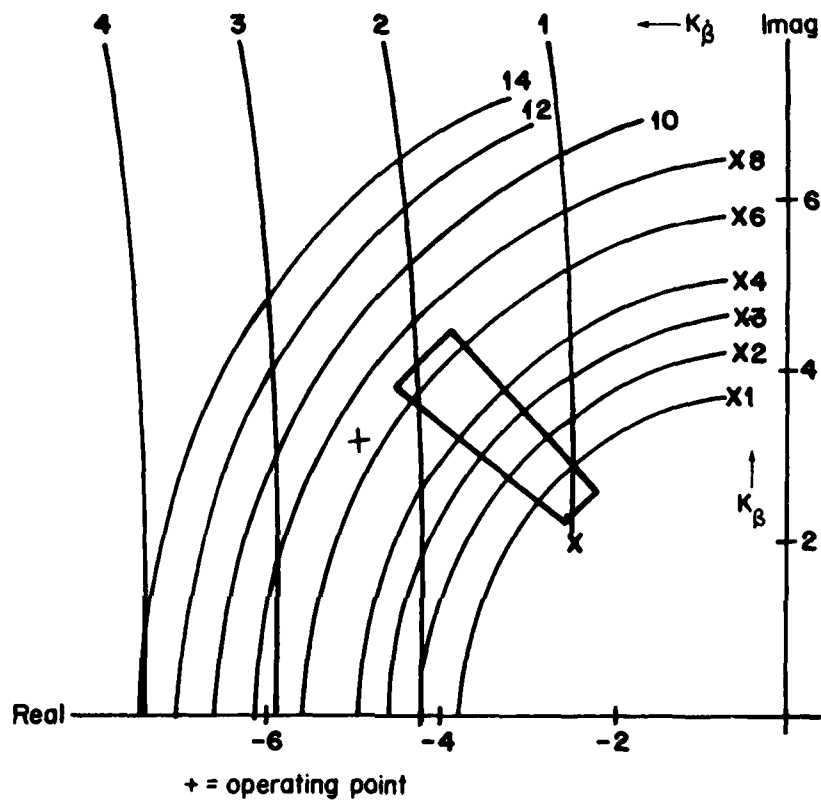
Figure 13c.   Root Map at Mach .7, 10000 Feet
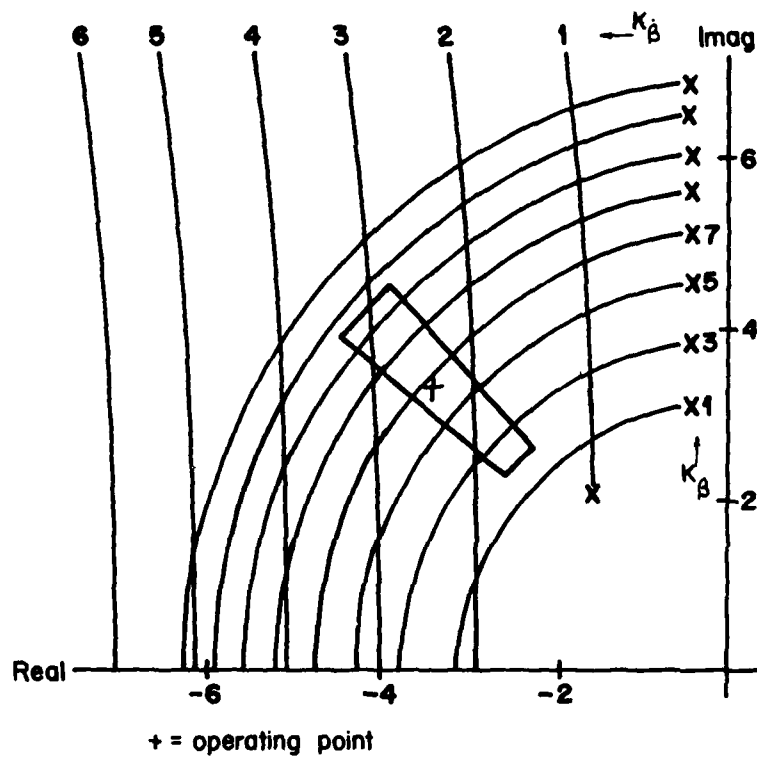
Figure 13d.   Root Map at Mach .6, 15000 Feet
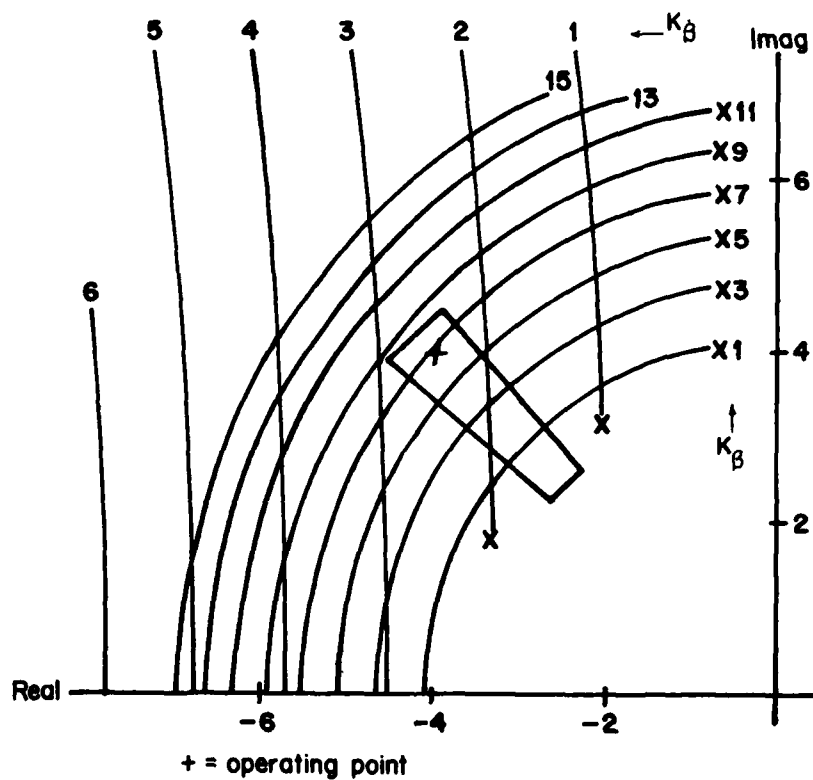
Figure 13e.   Root Map at Mach .9, 15000 Feet
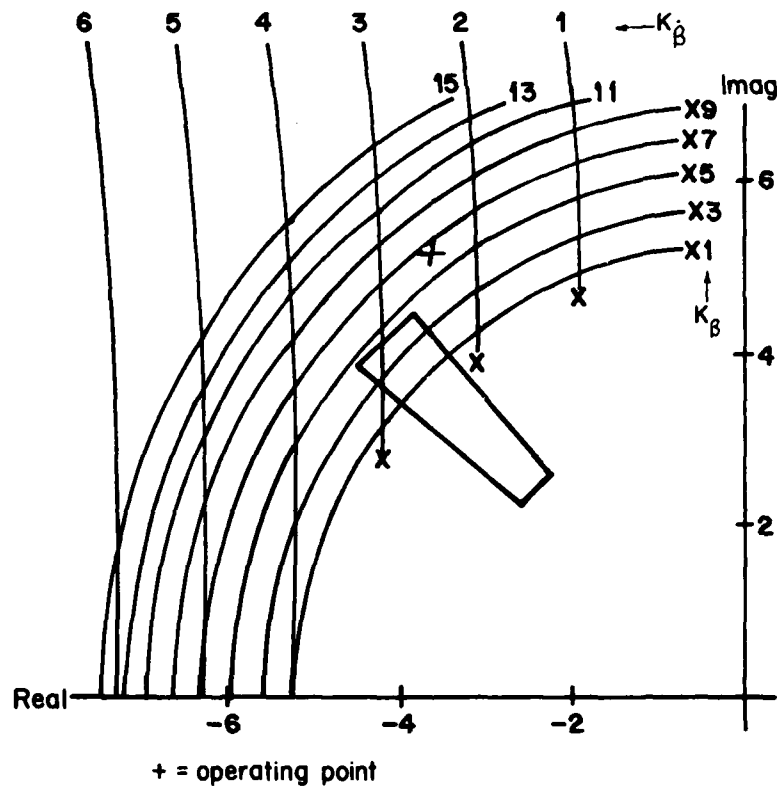
Figure 13f.   Root Map at Mach 1.2, 15000 Feet
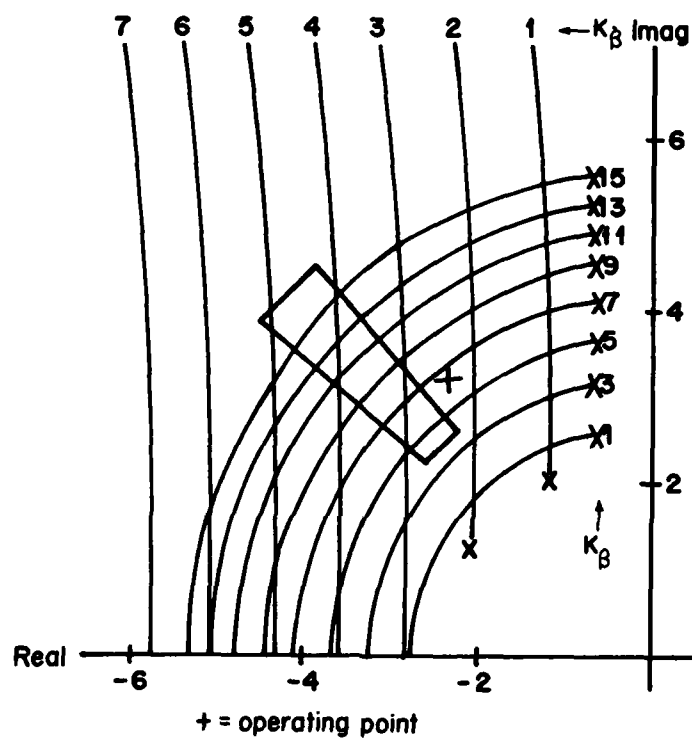
Figure 13g.   Root Map at Mach .6, 30000 Feet
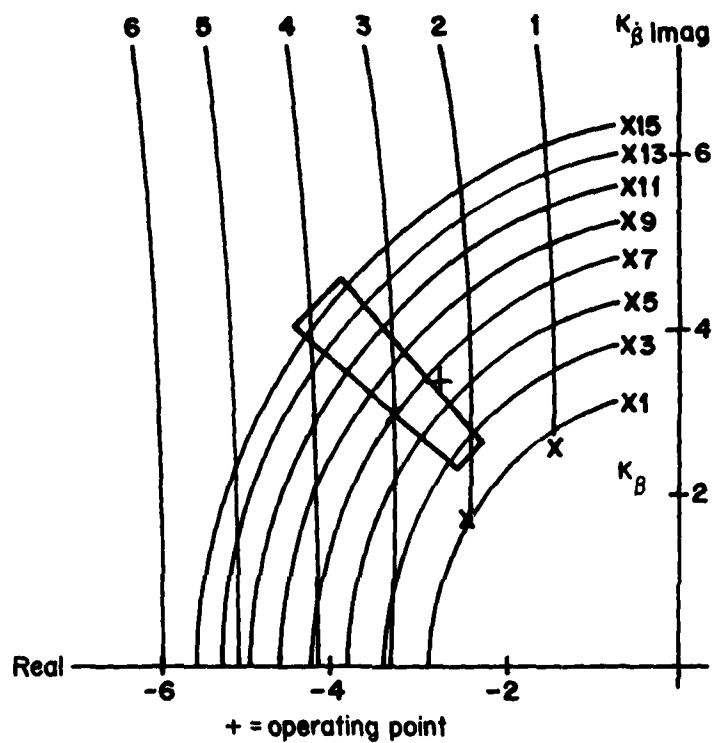
Figure 13h.   Root Map at Mach .9, 30000 Feet
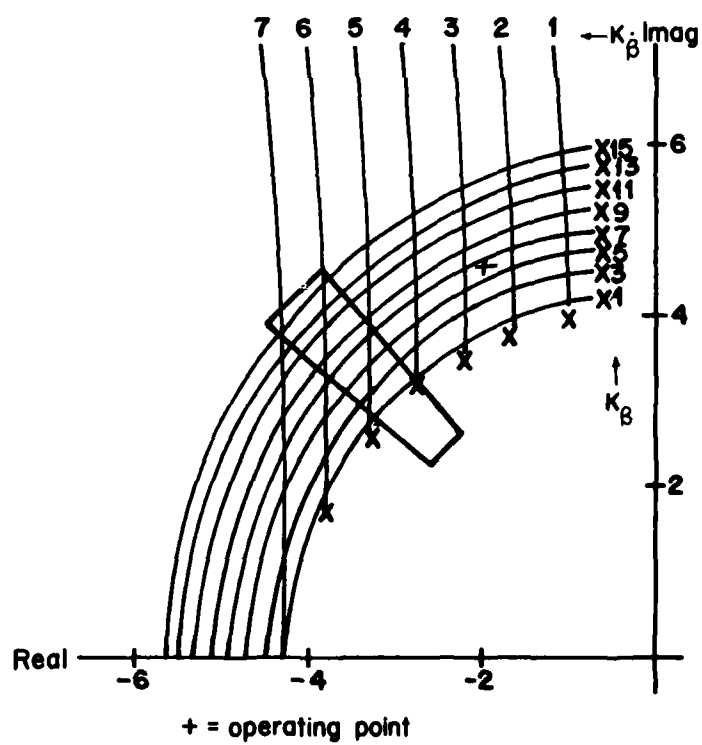
Figure 13i.   Root Map at Mach 1.4, 30000 Feet

To simplify the design, the option of gain scheduling K_β and $K_{\dot\beta}$ is eliminated. This means that the values of K_β and $K_{\dot\beta}$ should be set to obtain an adequate response throughout the envelope but, if possible, a good response at flight conditions typical for ATA tracking. ATA tracking typically occurs at high subsonic Mach numbers at low and middle altitudes. Using this somewhat subjective criterion, values of K_β and $K_{\dot\beta}$ were chosen as 6.5 and 2.5, respectively. These values are shown on the root maps as the operating gains. Table 2 shows the response of the aircraft in terms of damping and natural frequency at these operating gains.

TABLE 2

F-106 RESPONSE AT K_β = 6.5 AND $K_{\dot\beta}$ = 2.5

Map	Mach, Altitude	Damping Ratio	Natural Frequency (rad/sec)
Figure 13a	.4, S.L.	.71	4.5
Figure 13b	.9, S.L.	.79	6.6
Figure 13c	.7, 10000	.86	5.8
Figure 13d	.6, 15000	.67	4.8
Figure 13e	.9, 15000	.71	5.6
Figure 13f	1.2, 15000	.6	6.4
Figure 13g	.6, 30000	.6	4.0
Figure 13h	.9, 30000	.68	4.4
Figure 13i	1.4, 30000	.4	5.0

Table 2 shows that the chosen gains for K_β and $K_{\dot\beta}$ of 6.5 and 2.5 do provide a good response at the lower altitude, subsonic flight conditions. At the two supersonic conditions, however, the response is somewhat underdamped. This tendency of an underdamped response at supersonic Mach numbers should not be important since almost no tracking is done supersonically.

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3.   FREQUENCY RESPONSE ANALYSIS

The preliminary design of the β-$\dot{\beta}$ system using the model from Figure 10 shows that acceptable responses can be achieved using gains of 6.5 and 2.5 for K_β and $K_{\dot{\beta}}$. This acceptability criteria is based subjectively on the values of dutch roll damping and natural frequency. Since these gains come from the root map analysis, which assumes a second-order-linear aircraft model, it is appropriate to look at these gains in a more sophisticated model. The EASY Dynamic Analysis Program (Reference 2) is used to achieve this more elaborate model. Appendix C contains a short description of the EASY program and contains the input data for the frequency analyses.

The EASY program was used to obtain closed-loop frequency plots for the following transfer functions: $\beta/\delta r$, $\phi/\delta r$, $\beta/\delta a$. These plots are shown for flight conditions of Mach .8 at 10000 feet and Mach .6 at 30000 feet. The first condition is somewhat typical of an ATA engagement and the second is representative of a low dynamic pressure situation for the aircraft. The three transfer functions above are chosen specifically because each shows information significant to the ATA tracking task. The frequencies of greatest importance for ATA tracking are those around the dutch roll frequency. These frequencies are important because the dutch roll mode is continually being excited during tracking. The frequencies range from about two to seven rad/sec depending on control system and flight condition. $\beta/\delta r$ gives an indication of the ease with which the pilot can point the aircraft using the rudder. $\phi/\delta r$ shows the coupling effect of rudder into roll angle and it can also give an indication of the ease with which the pilot can point the aircraft. An aircraft with a control system designed to facilitate ATA tracking should have a large magnitude for $\beta/\delta r$ (near 0 db) to provide adequate pointing capability while maintaining a low magnitude for $\phi/\delta r$, or low roll/sideslip coupling. The effect of a large $\phi/\delta r$ would be an increase in pilot workload due to the inadvertent roll angles. $\beta/\delta a$ is an indicator of how well the aircraft is maintaining coordinated flight, or equivalently, how precisely the aircraft is rolling about the velocity vector. A low magnitude for $\beta/\delta a$ is most advantageous for ATA tracking.

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The closed-loop frequency plots for the two flight conditions are shown for the bare airframe, standard SAS, and β-$\dot{\beta}$ SAS. Figures 14a - 14c and Figures 15a - 15c show the frequency response for $\beta/\delta r$ for both flight conditions. The plots show that the desirable quality of a relatively large $\beta/\delta r$ is achieved by both the bare airframe and the β-$\dot{\beta}$ SAS at both flight conditions. Figures 16a - 16c and Figures 17a - 17c show $\phi/\delta r$ at the two flight conditions. The bare airframe $\phi/\delta r$ is unacceptably large, but the standard SAS and the β-$\dot{\beta}$ SAS both have much lower magnitudes and are therefore more desirable. This same desirable quality of low coupling magnitude is also shown by the standard and β-$\dot{\beta}$ SAS's in their $\beta/\delta a$ frequency plots. These frequency plots are shown in Figures 18a - 18c and Figures 19a - 19c.

Based on these frequency plots, the bare airframe is obviously least desirable for ATA tracking due to its large $\phi/\delta r$ and $\beta/\delta a$ ratios. On the other hand the standard SAS and the β-$\dot{\beta}$ SAS have much smaller magnitudes for $\beta/\delta a$ and $\phi/\delta r$ and therefore are probably more applicable to ATA tracking. The β-$\dot{\beta}$ SAS shows a larger magnitude $\beta/\delta r$ than the standard SAS, possibly making it easier for the pilot to point the aircraft, but the standard SAS has smaller $\phi/\delta r$ and $\beta/\delta a$ coupling magnitudes, possibly decreasing pilot workload. In summary, the bare airframe is probably not adequate for the tracking task while both the standard and β-$\dot{\beta}$ SAS's appear to be about equal in their capabilities.

4. DETAILED DESIGN MODEL

The preliminary design model from Figure 12 provided a basis for the engineering analysis of the β-$\dot{\beta}$ control. A more detailed model is now presented which includes "real world" criteria in its design. The very first question asked on seeing the preliminary design model is, "Can β and $\dot{\beta}$ be measured?" The answer is yes for the sideslip angle. Beta vanes provide adequate, though somewhat noisy, measurements of β. Sideslip angle rate, on the other hand, is not so easily measured. The beta signal is too noisy to differentiate; hence, some other source for $\dot{\beta}$ must be found.

Figure 14a.   Bare Airframe Beta/Delta Rudder .8, 15000

Figure 14b. Standard SAS Beta/Delta Rudder .8, 10000
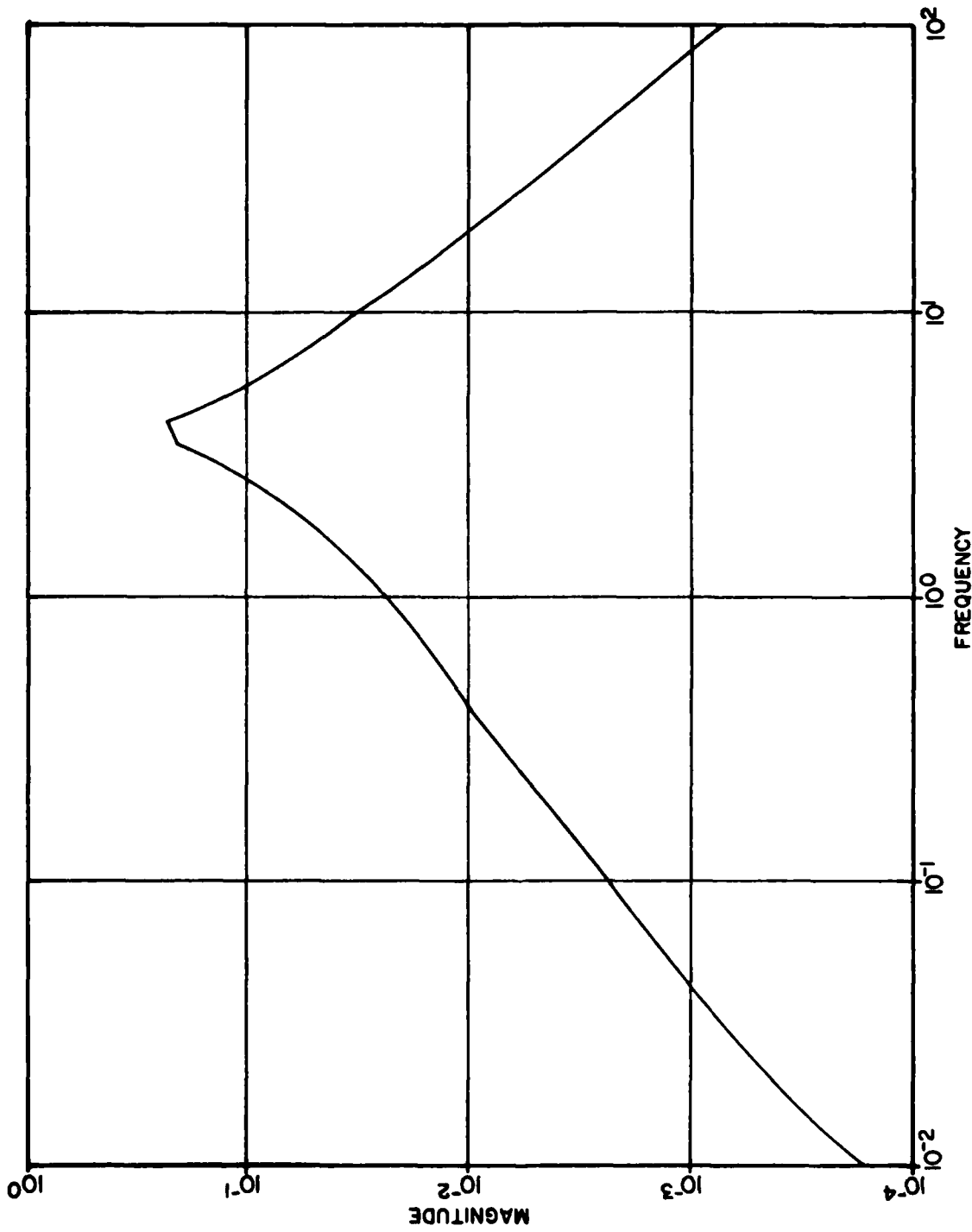
Figure 14c.   Betadot SAS Beta/Delta Rudder .8, 10000
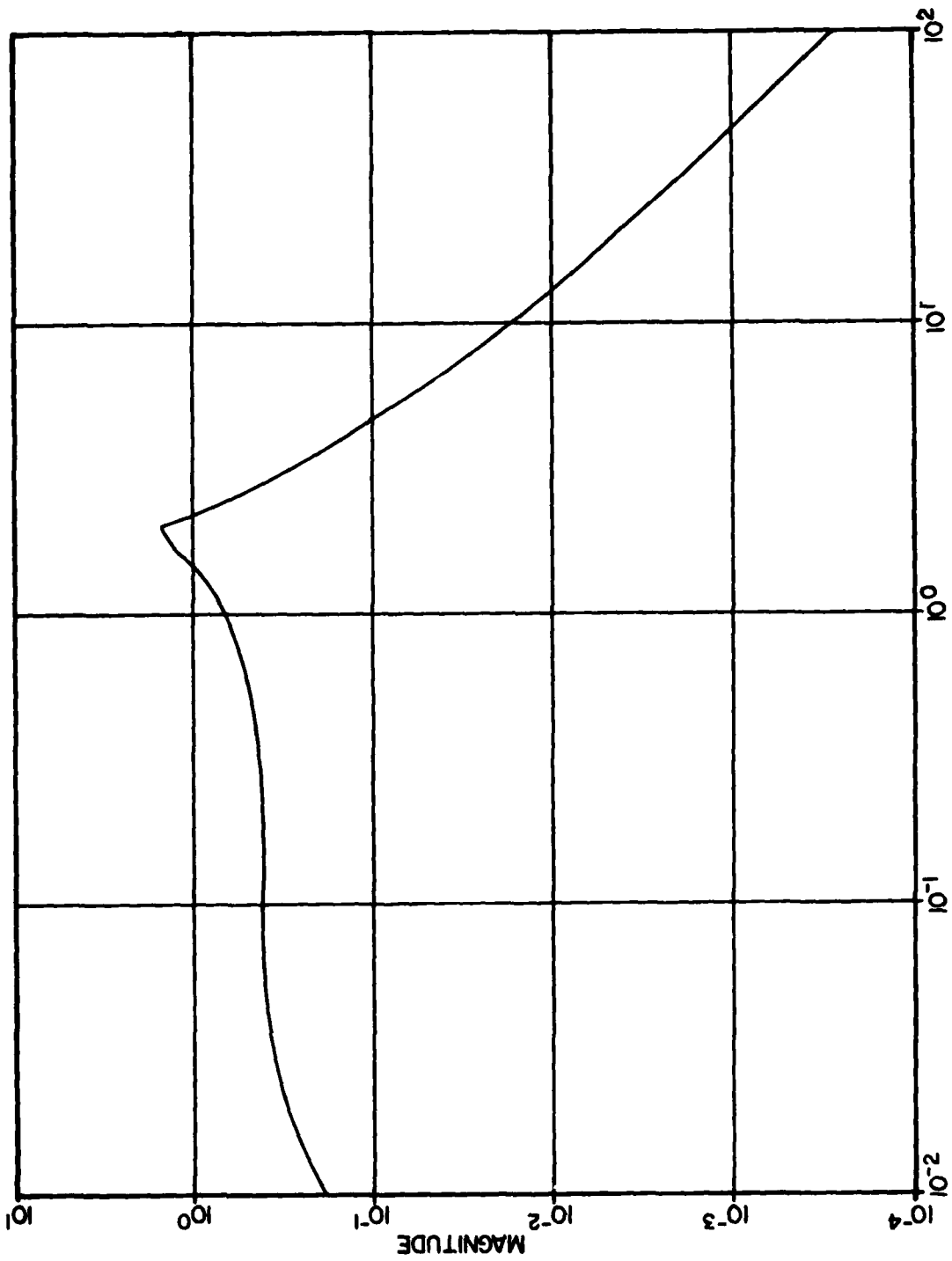
Figure 15a.   Bare Airframe Beta/Delta Rudder .6, 30000
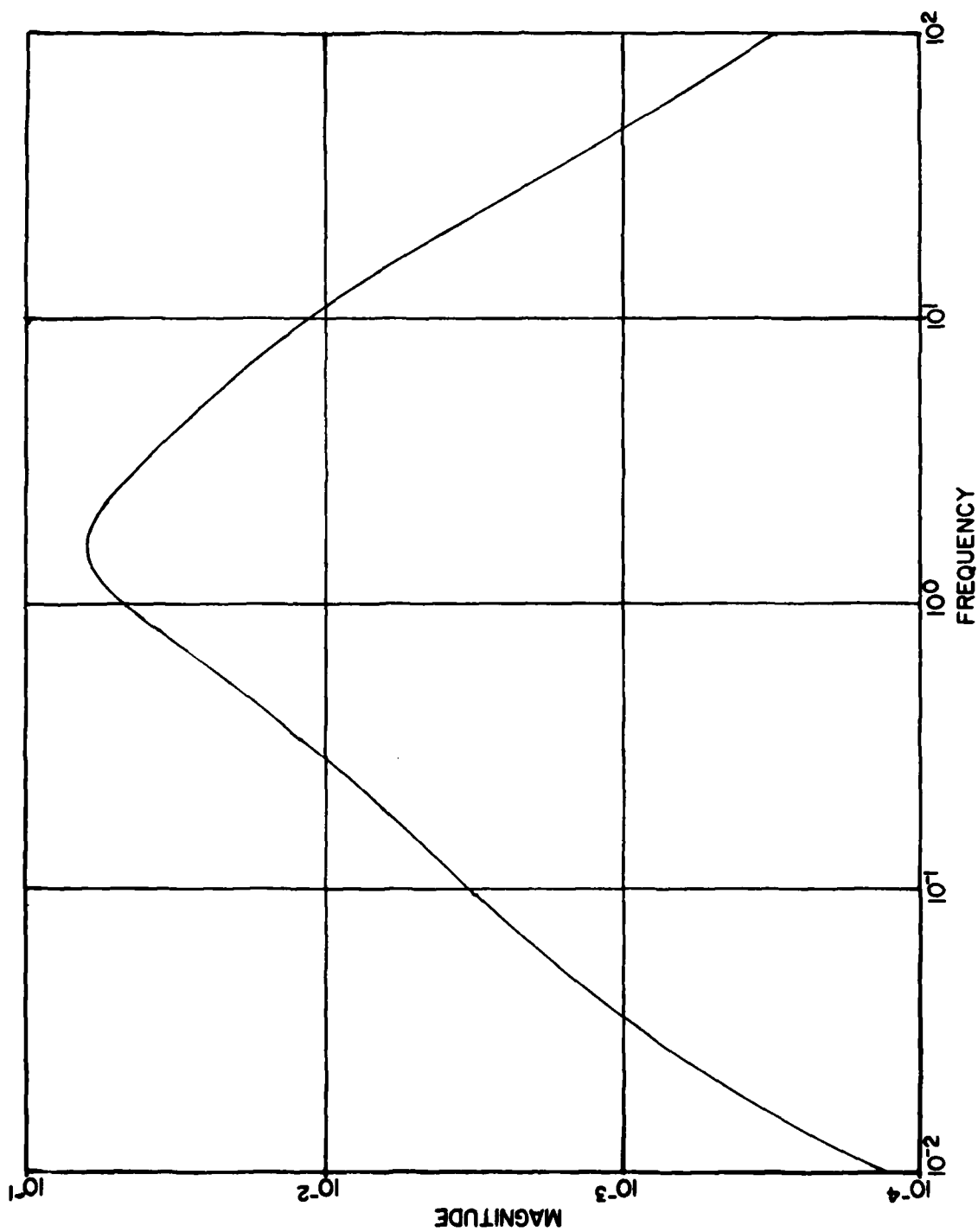
Figure 15b. Standard SAS Beta/Delta Rudder .6, 30000
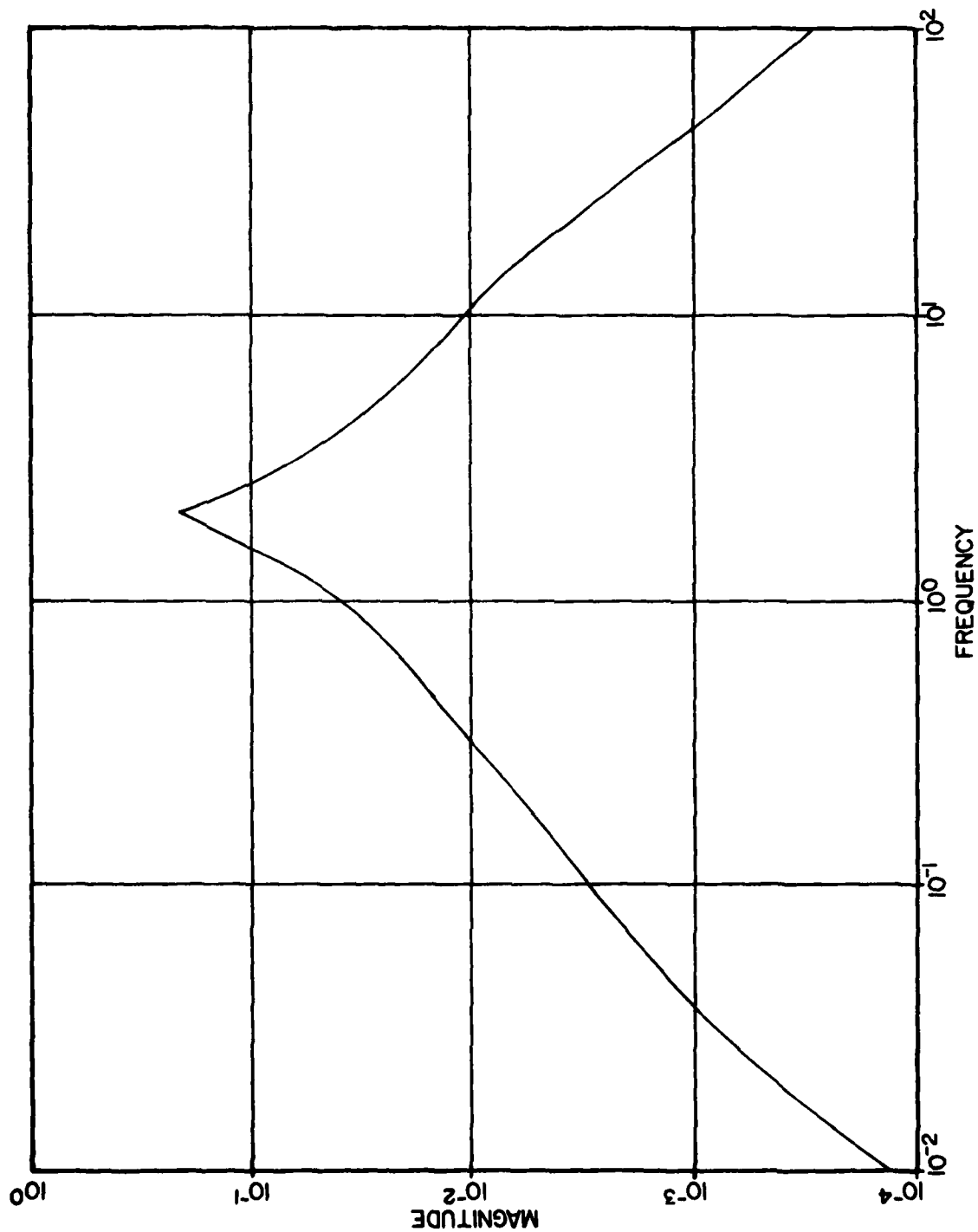
Figure 15c. Betadot SAS Beta/Delta Rudder .6, 30000
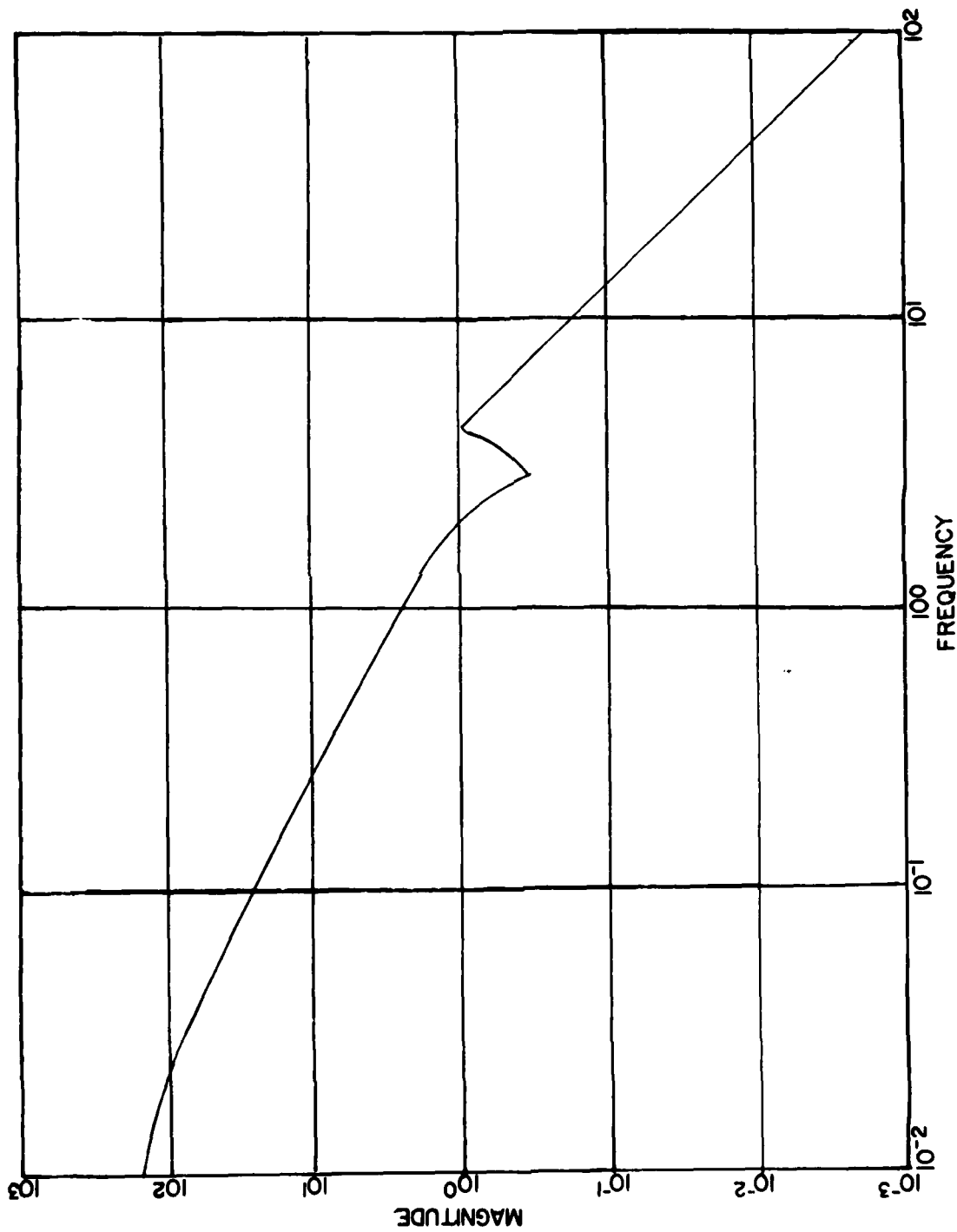
Figure 16a. Bare Airframe Phi/Delta Rudder .8, 10000
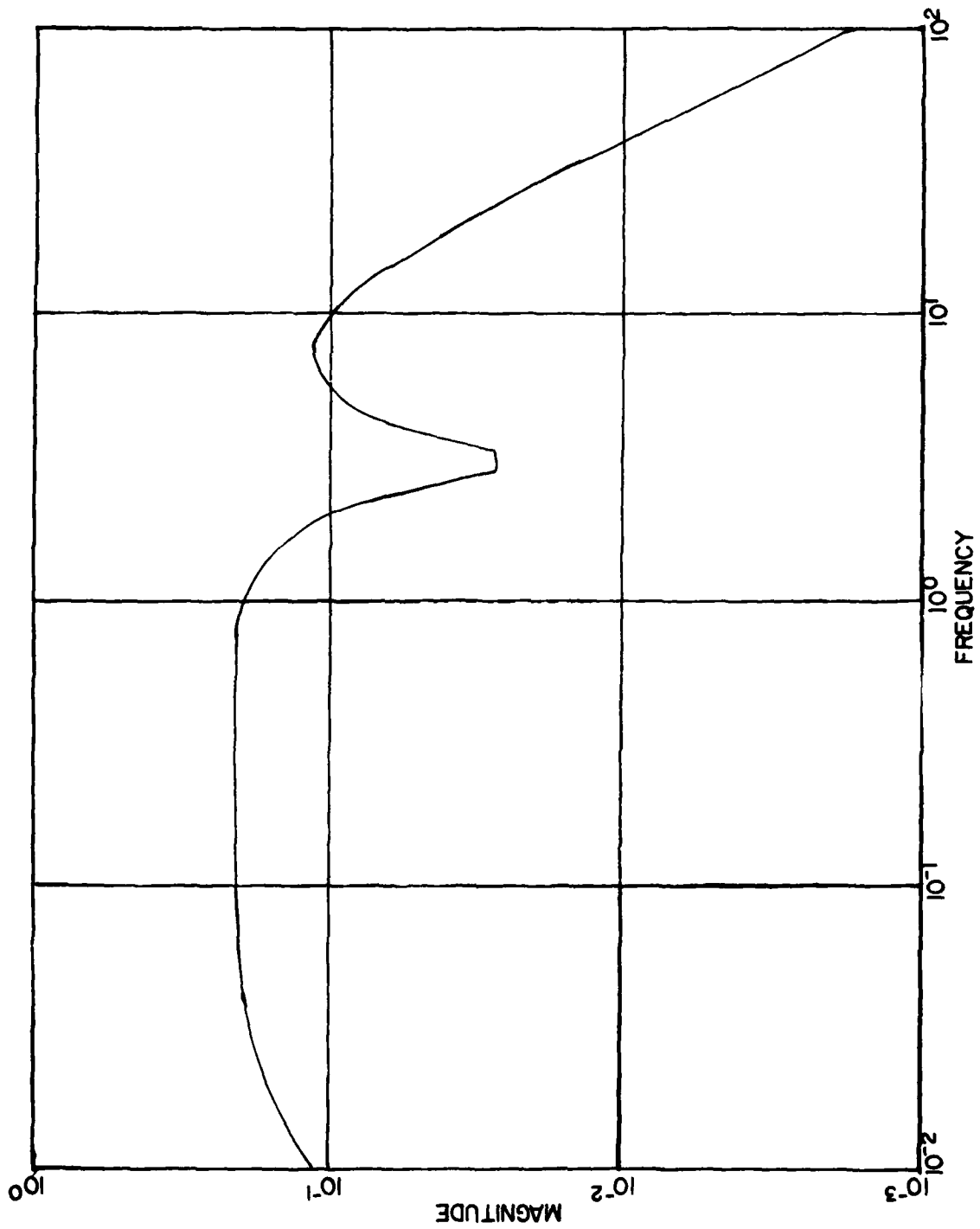
Figure 16b. Standard SAS Phi/Delta Rudder .8, 10000

FREQUENCY

MAGNITUDE
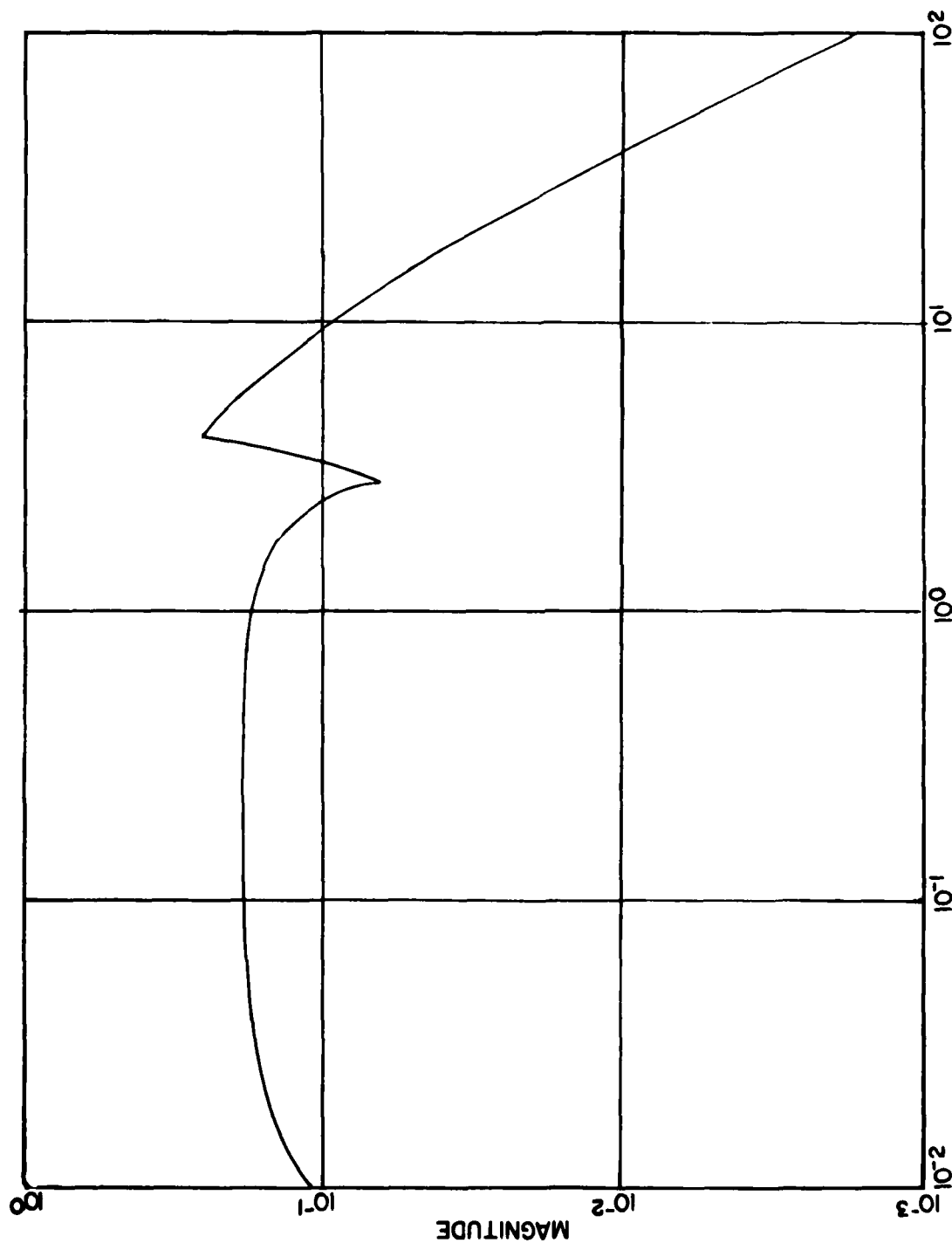
Figure 16c. Betadot SAS Phi/Delta Rudder .8, 10000
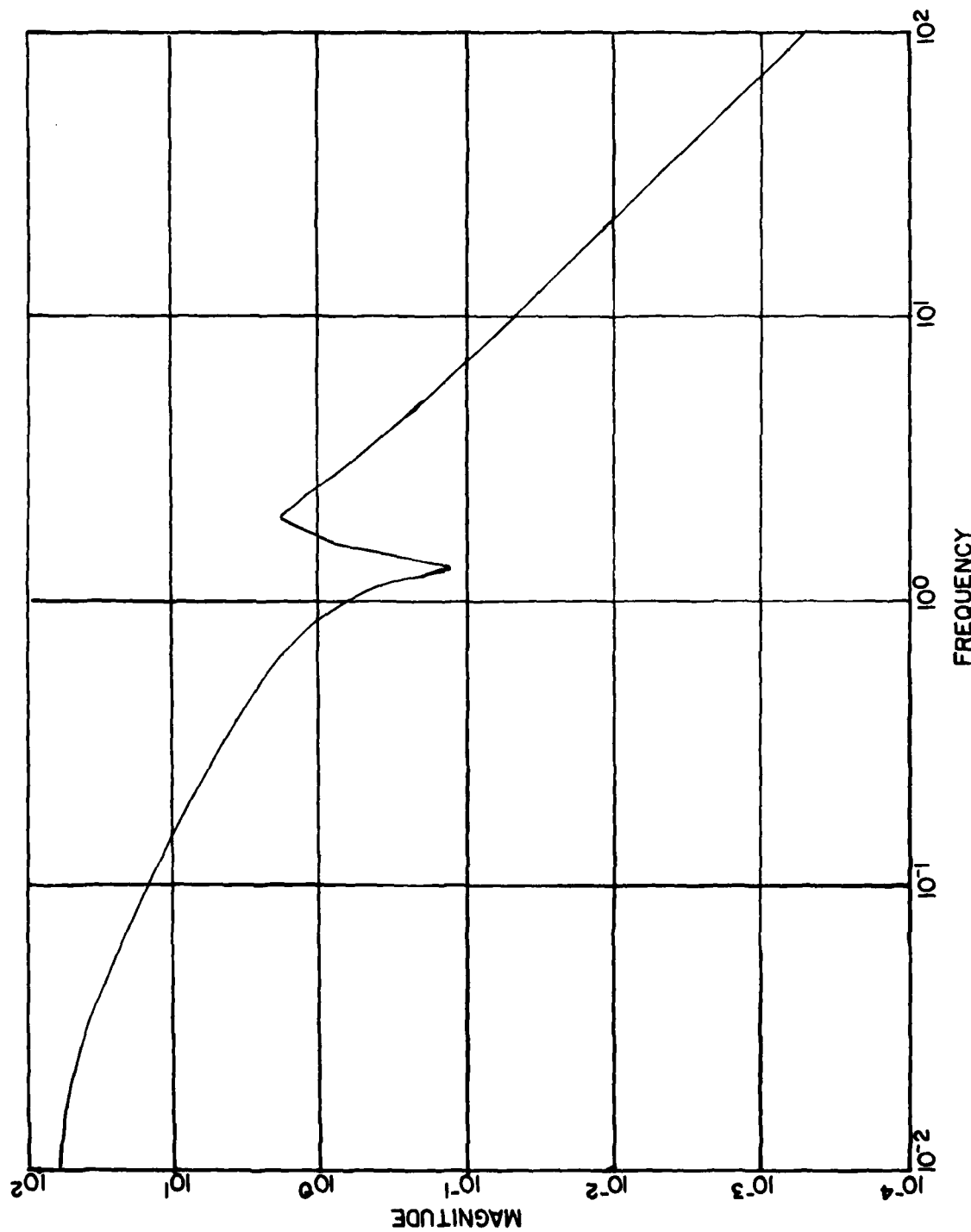
Figure 17a. Bare Airframe Phi/Delta Rudder .6, 30000
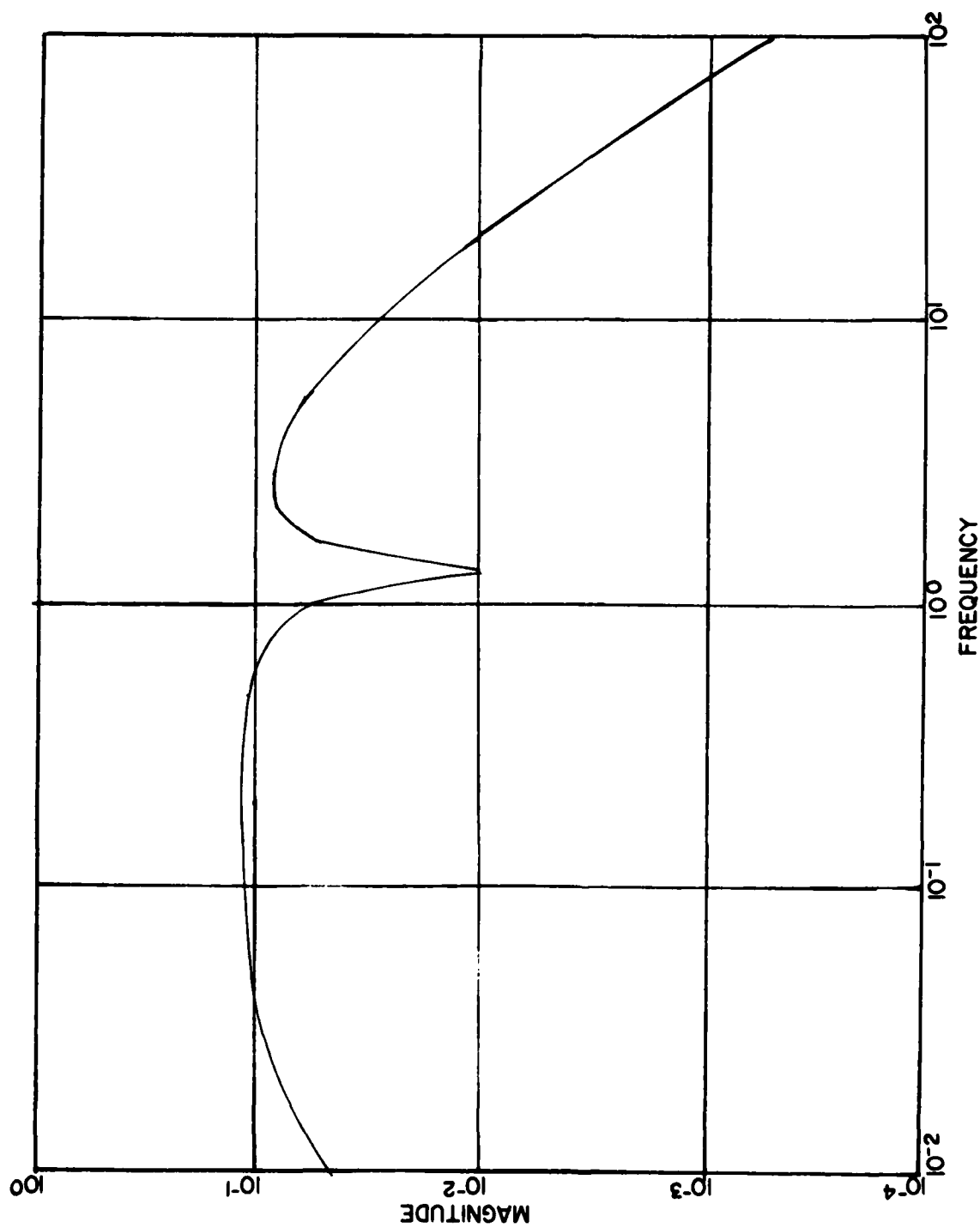
Figure 17b. Standard SAS Phi/Delta Rudder .6, 30000

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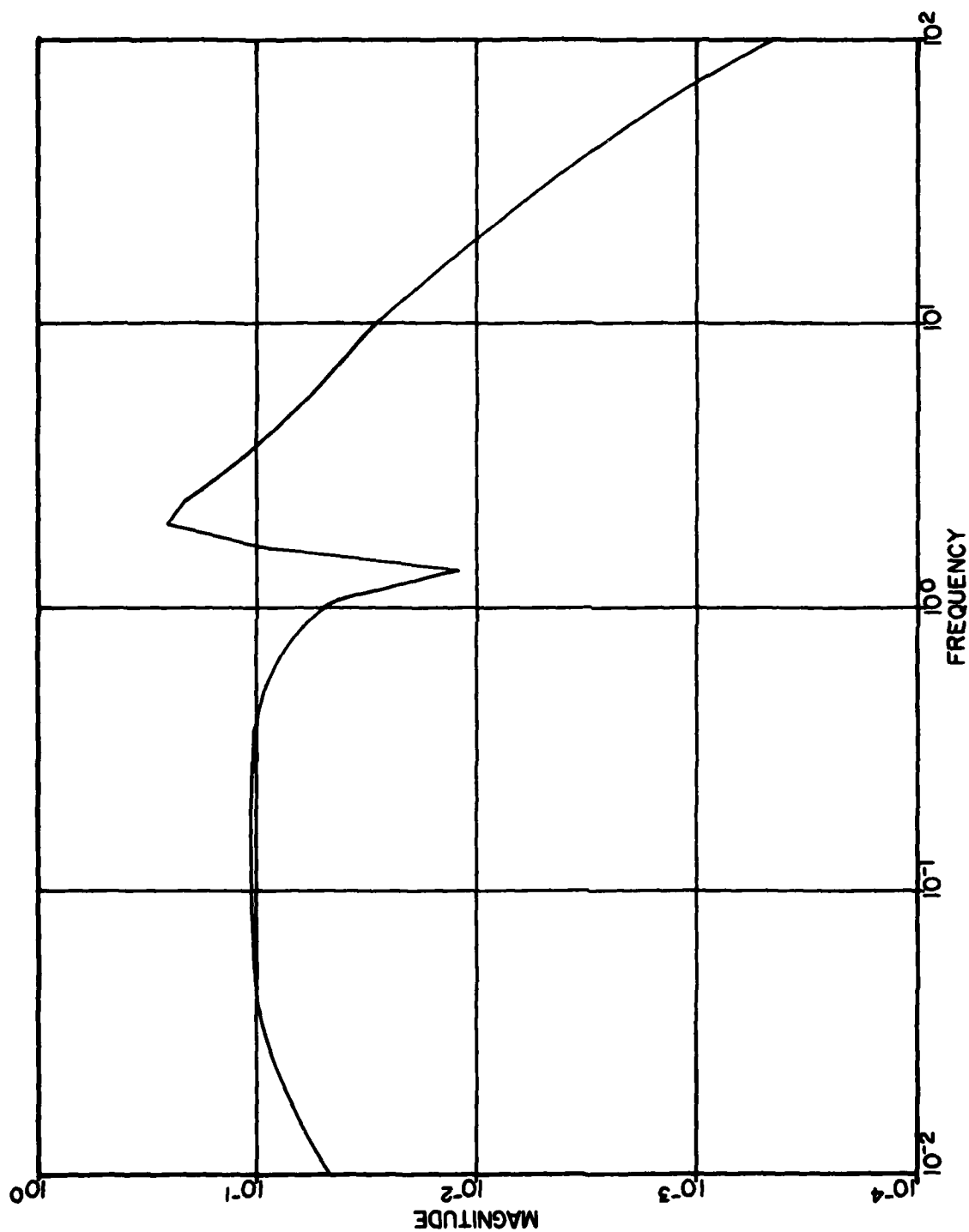
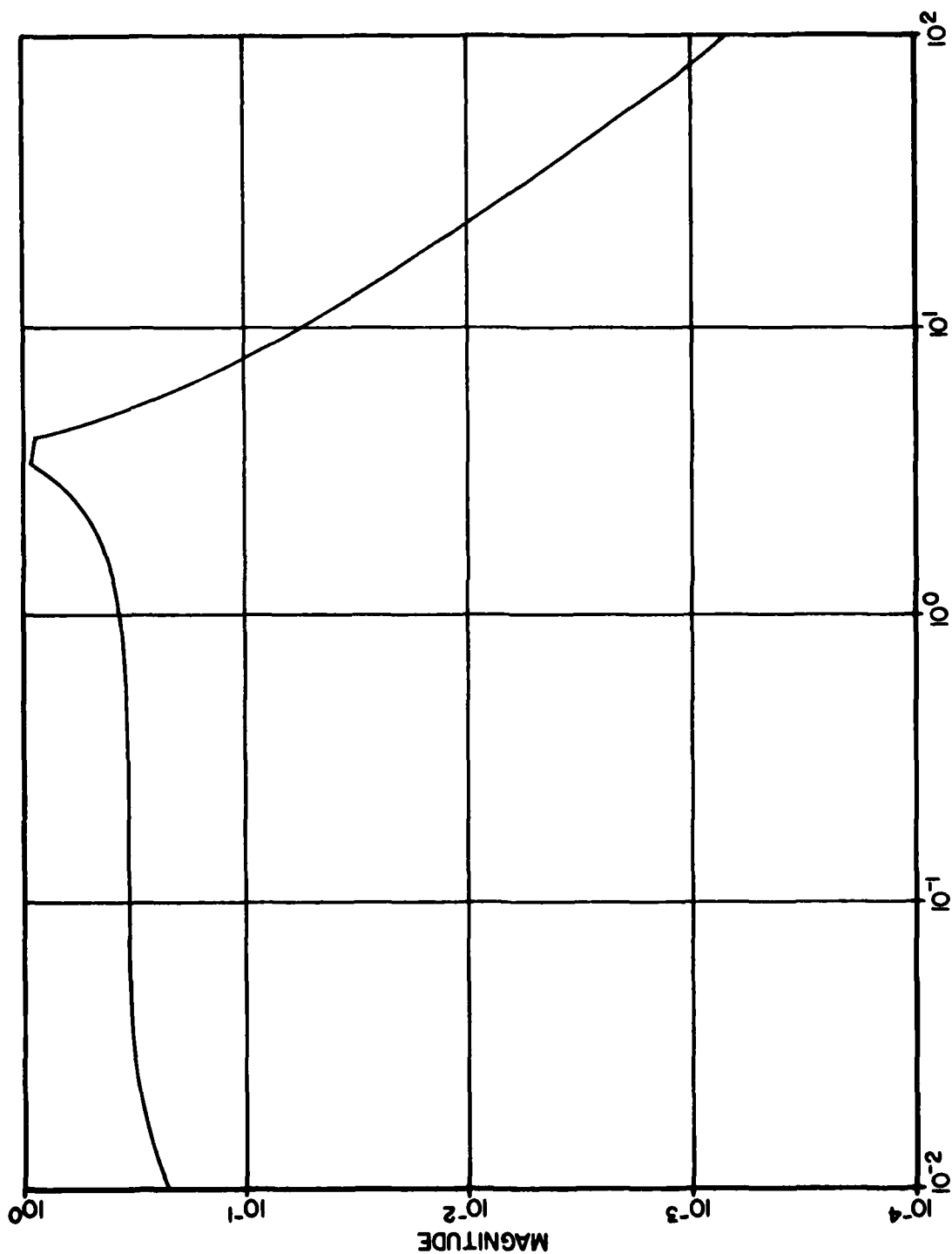Figure 17c. Betadot SAS Phi/Delta Rudder .6, 30000

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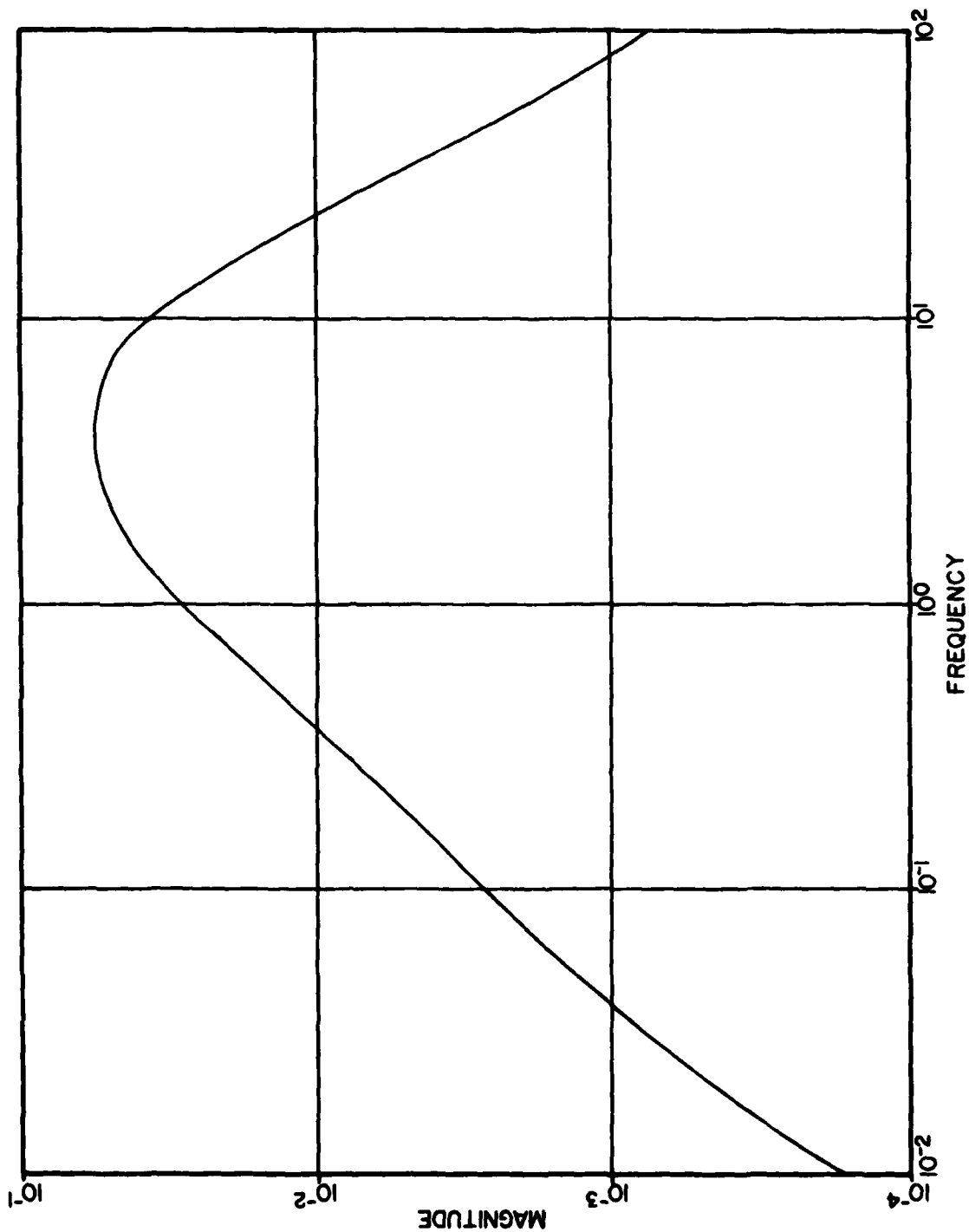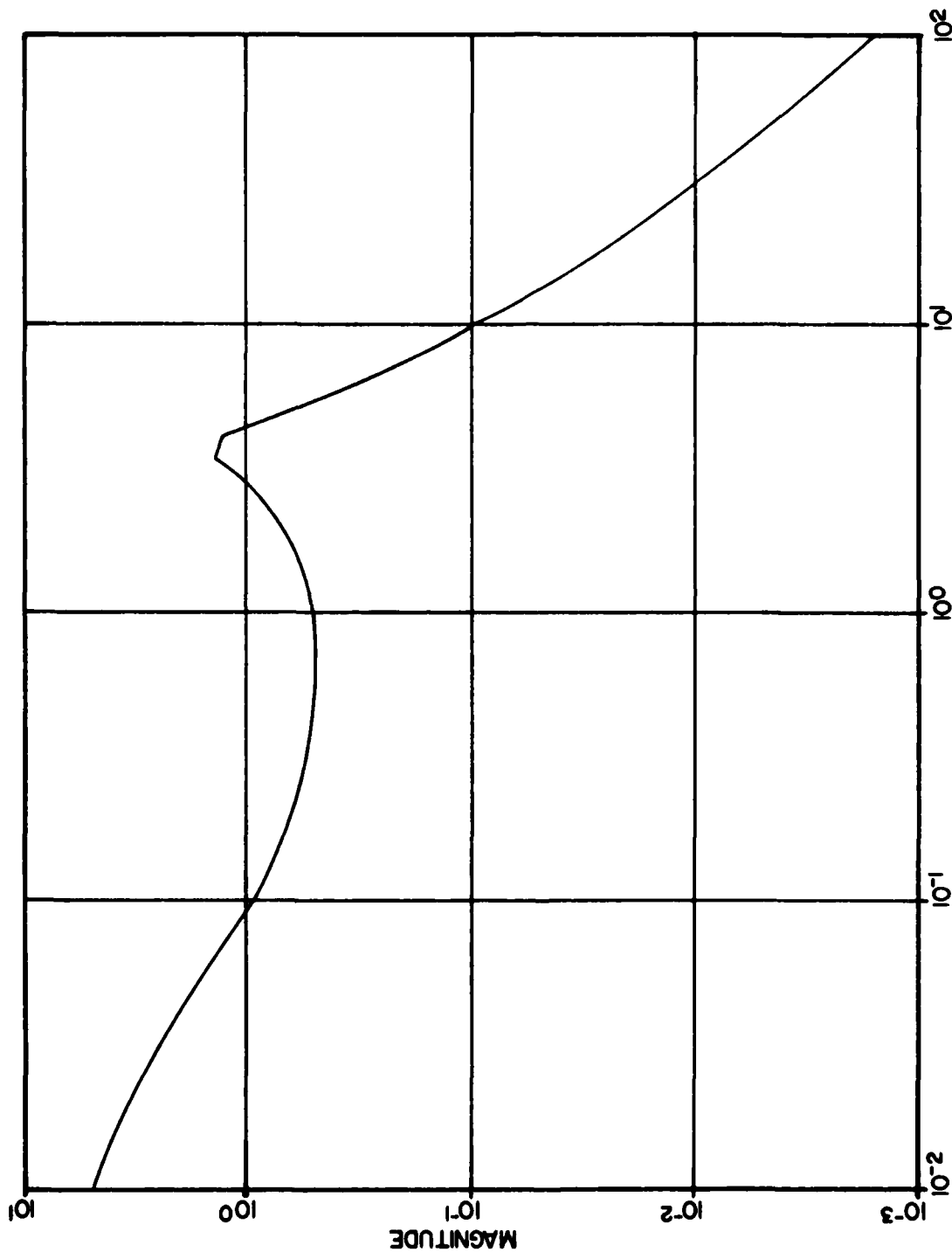Figure 18a. Bare Airframe Beta/Delta Aileron .8, 10000
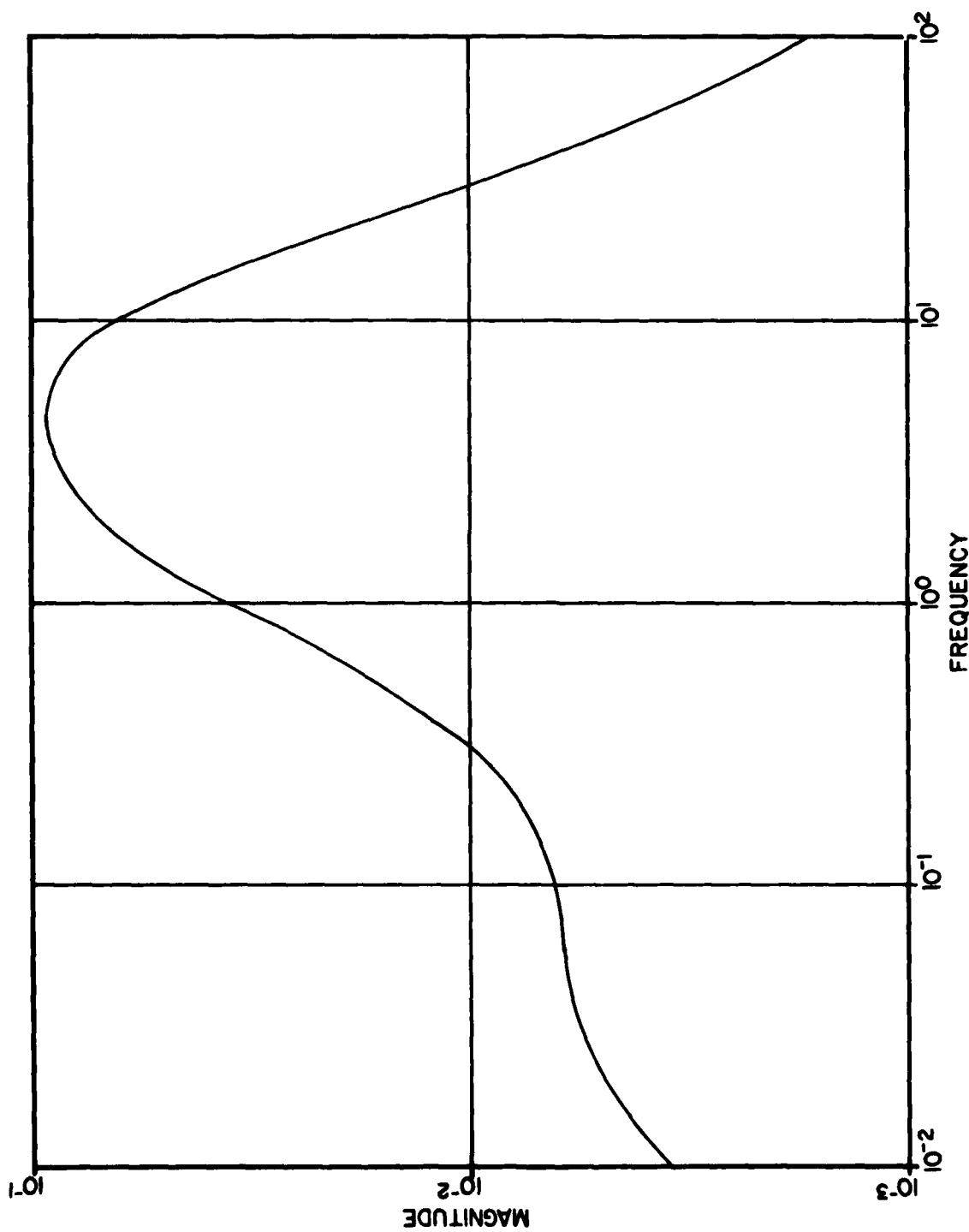
Figure 18b. Standard SAS Beta/Delta Aileron .8, 10000
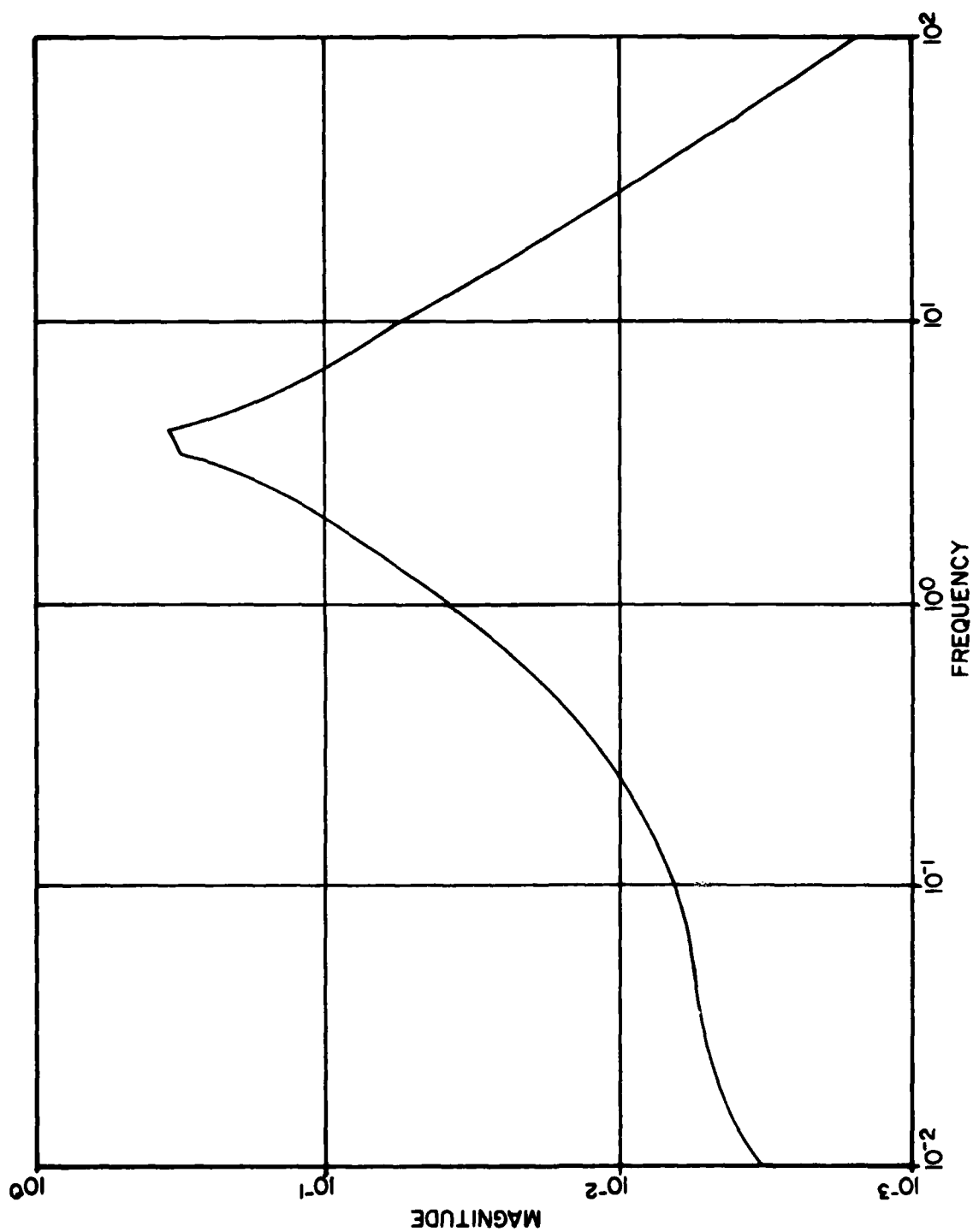
Figure 18c. Betadot SAS Beta/Delta Aileron .8, 10000
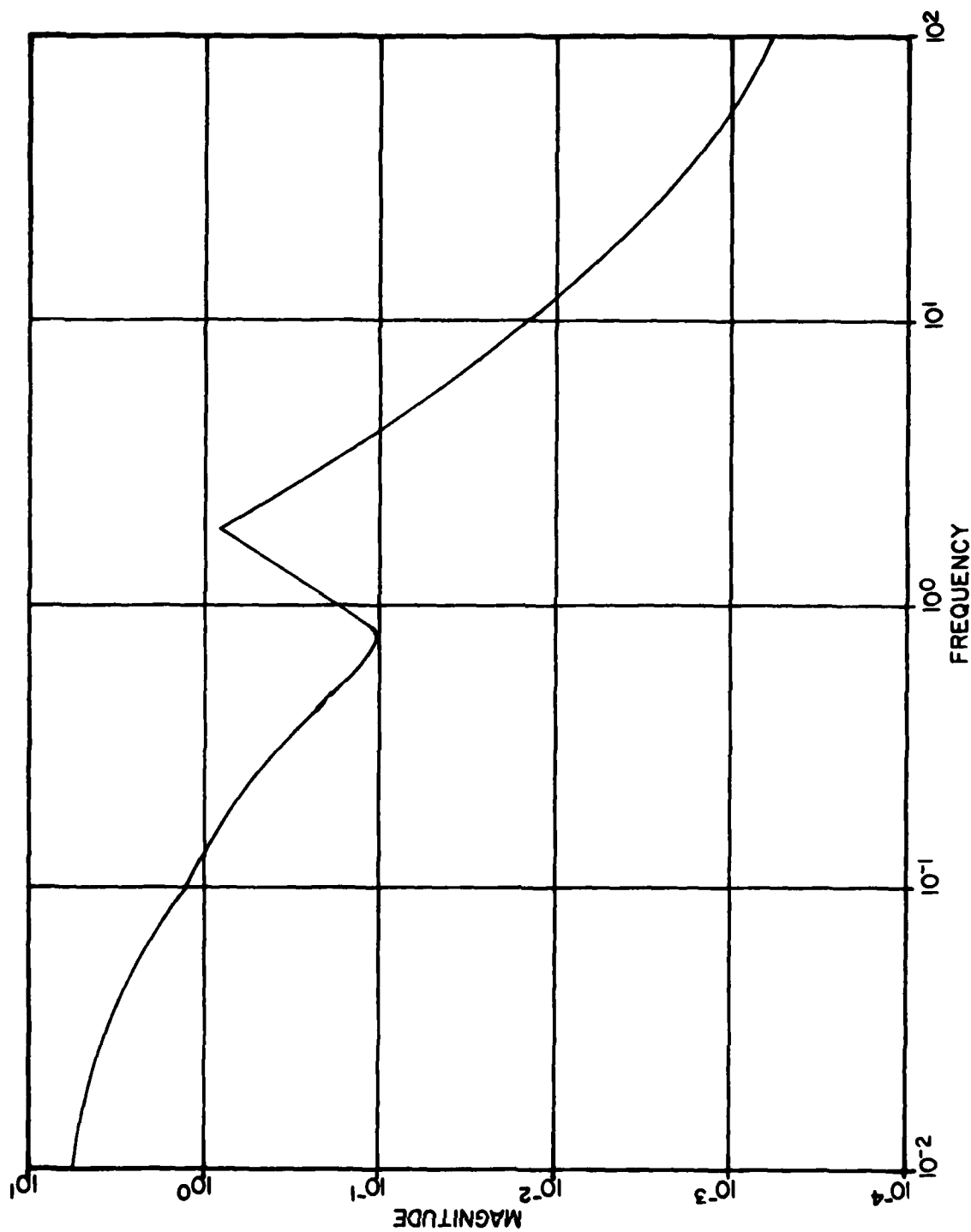
Figure 19a. Bare Airframe Beta/Delta Aileron .6, 30000
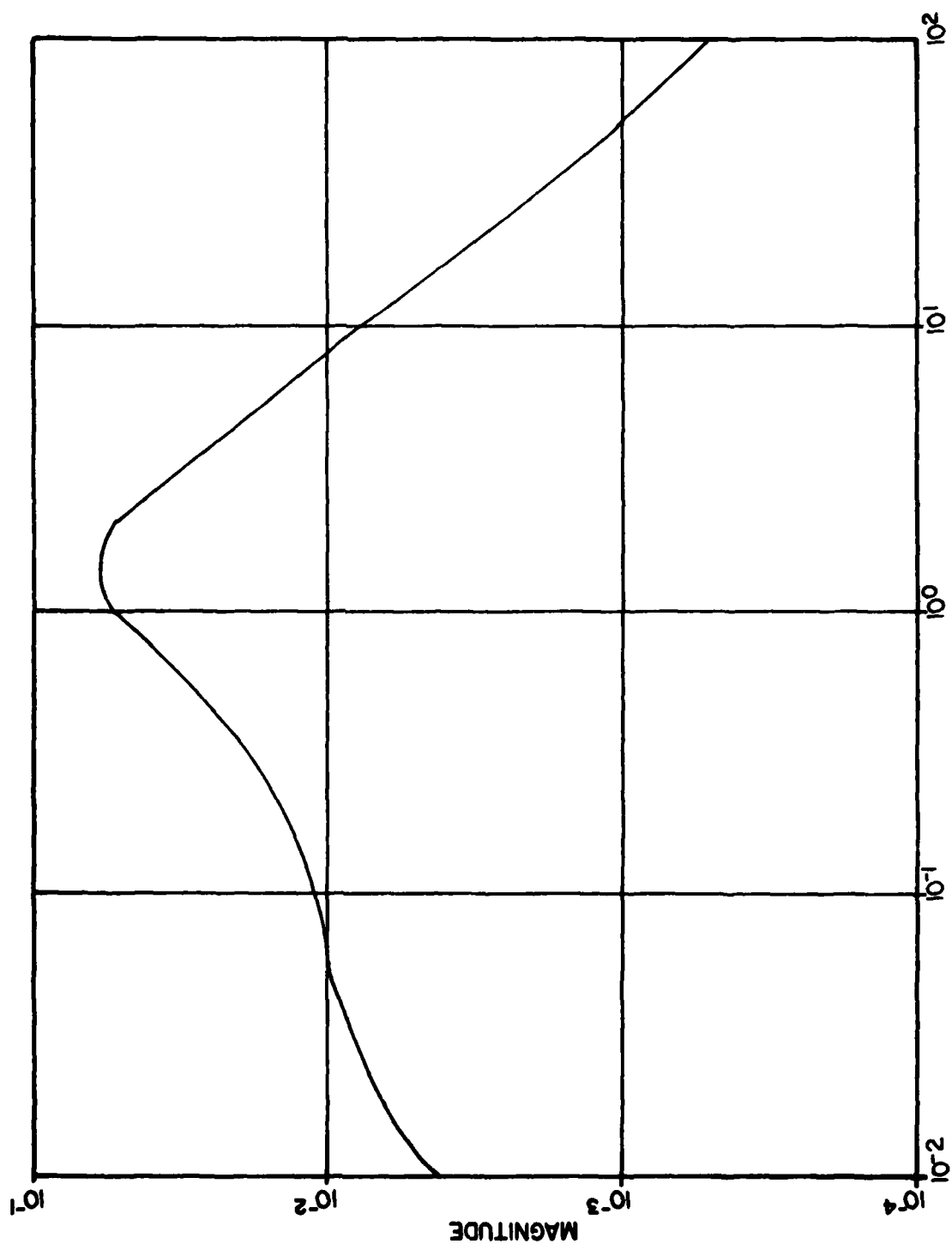
Figure 19b. Standard SAS Beta/Delta Aileron .6, 30000
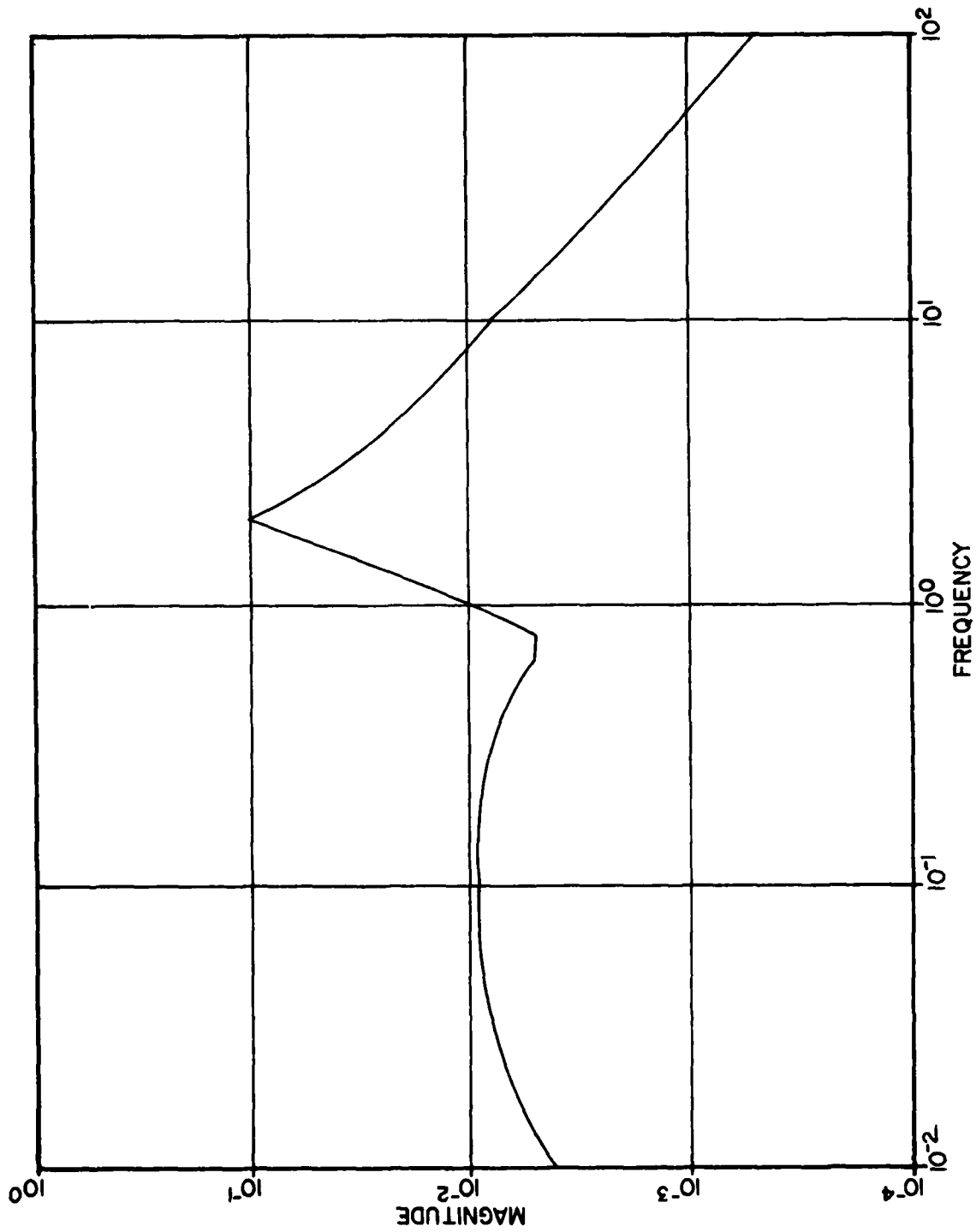
Figure 19c. Betadot SAS Beta/Delta Aileron .6, 30000

Using the definition of β, an approximation of $\dot{\beta}$ can be derived which consists of parameters measurable on the F-106. Appendix D shows this derivation which provides an approximate, through fairly accurate, synthesis of $\dot{\beta}$. The synthesized $\dot{\beta}$ is shown below:

$$\dot{\beta} = p\alpha - r + \frac{A_{y_{acc}}}{U} + \frac{g}{U}\cos\theta\sin\phi$$

p = roll rate (rad/sec)

α = angle of attack (rad)

r = yaw rate (rad/sec)

$A_{y_{acc}}$ = accelerometer lateral acceleration

U = true airspeed (ft/sec)

g = gravity constant (32.174 ft/sec^2)

θ = pitch angle (rad)

ϕ = roll angle (rad)

Based on this synthesis of $\dot{\beta}$, a detailed design of the system is shown in Figure 20. Figure 20 includes the ± 6 degree hardware limits present on the existing F-106 SAS as well as a complementary filter on the β signal. This complementary filter, with time constant τ, allows high frequency components of β to come from the $\dot{\beta}$ signal. The electrical signal from the pilot comes from rudder pedal potentiometers and allows the pilot to command sideslip angle directly or, if K_β and K_I are zero, to command sideslip rate. A value of K_p, the pilot's gain, cannot be determined in this nonpiloted simulation. A proportional plus integral forward-loop compensator is included to get rid of the steady-state error caused by the feedbacks.

Figure 20. Detailed Design Model

This detailed design of the β-$\dot{\beta}$ SAS was programmed on the Aeronautical Systems Division Hybrid Computer to be compared to the present SAS. Use of the β-$\dot{\beta}$ system showed significant improvement in both sideslip perturbation and dutch roll damping. Figure 21 emphasizes the reduction of sideslip perturbation during a 60 degree roll at different flight conditions. The same response for the bare airframe and the standard SAS were shown previously in Figures 8 and 9. Figure 22 shows the increased speed of response and improved dutch roll damping provided by the β-$\dot{\beta}$ system.

Based on the hybrid simulation runs and previous root locus and frequency response results, Figure 20 shows the configuration of a fixed-gain β-$\dot{\beta}$ SAS which provides significantly better performance than the standard SAS in terms of sideslip perturbations due to roll, speed of response, and dutch roll damping. The system also uses signals realistically available on high performance aircraft, including the F-106.
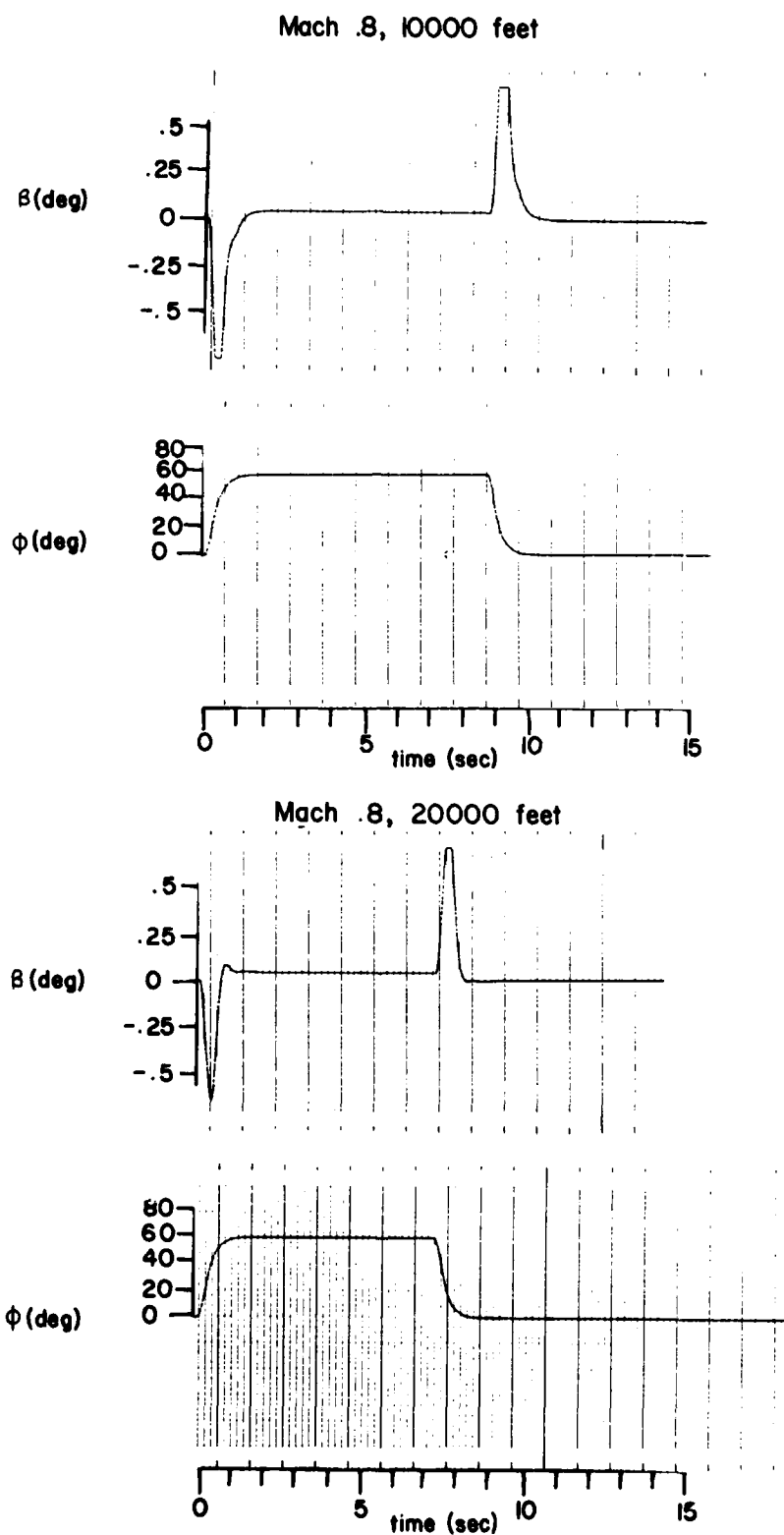
Figure 21. β-β̇ SAS Response to 60° Bank Angle
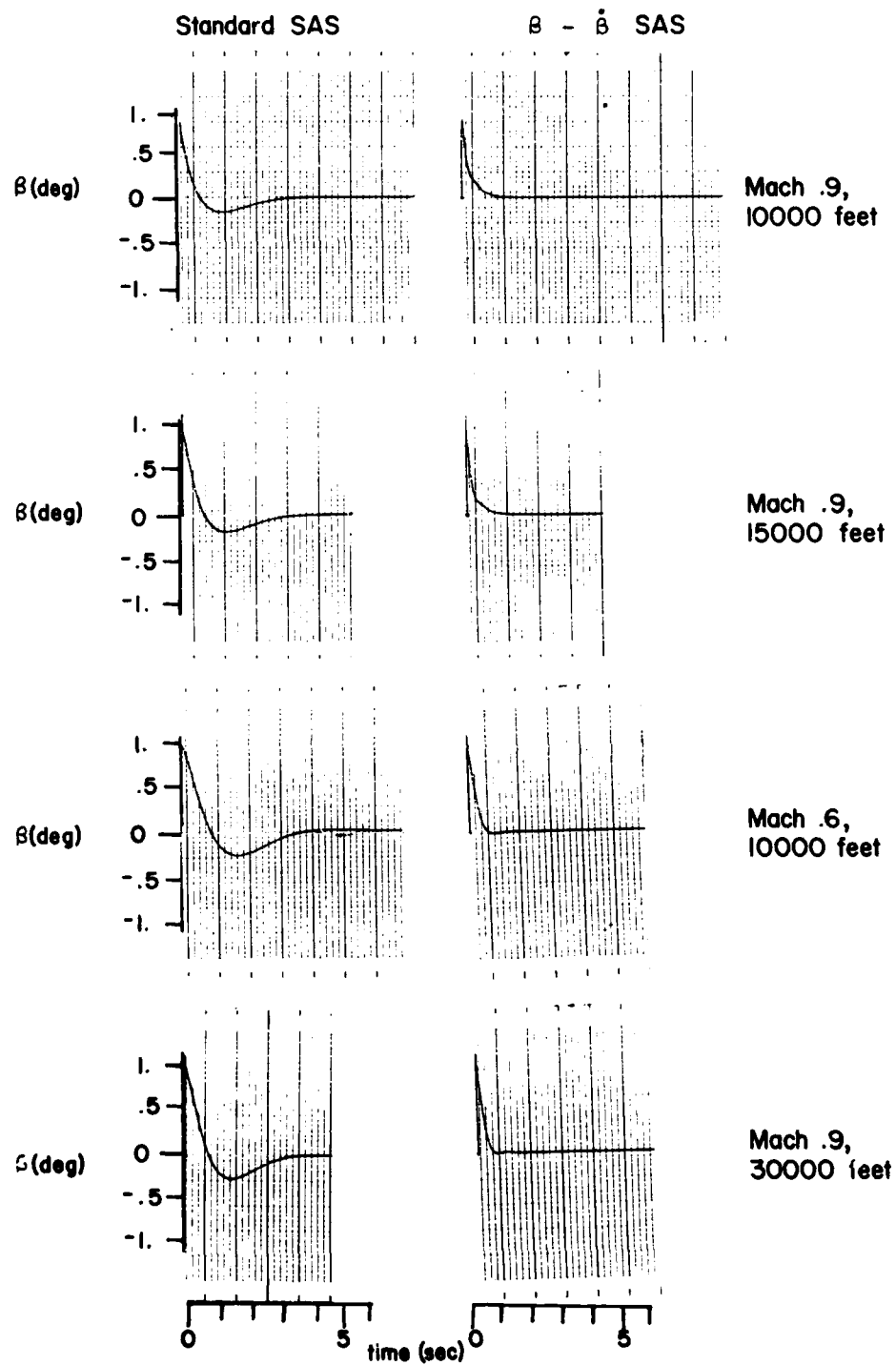
Figure 22. Response to One Degree Sideslip

SECTION IV

F-106 LAMARS SIMULATION

1. SIMULATION DESCRIPTION

Based on root locus, frequency response, and time response analysis methods, the β-$\dot{\beta}$ system appears superior to the standard SAS in terms of sideslip perturbations, speed of response, and dutch roll damping. None of these three measures of merit, however, can be considered the ultimate measure of the system's capability. The ultimate measure of merit is the pilot's ability to track another aircraft. To evaluate these systems using tracking performance as a measure of merit, a man-in-the-loop simulation was used. Using the Flight Dynamics Laboratory's Large Amplitude Multimode Aerospace Research Simulator (LAMARS), an experiment was conducted to evaluate the new system.

The experiment was set up to compare the standard SAS, from Figure 6, and two configurations of the β-$\dot{\beta}$ SAS, from Figure 20. One configuration is as shown in Figure 20 with $K_\beta = 6.5$ and $K_{\dot{\beta}} = 1.9$. The second configuration had K_β and K_I both set to zero with $K_{\dot{\beta}} = 1.9$. This configuration, the $\dot{\beta}$ system, allows only sideslip rate to be fed back to the rudder. This $\dot{\beta}$ system provides a sideslip rate control capability to the pilot. This configuration is included because the pilots are most familiar with rate control which is provided by the standard SAS. The $\dot{\beta}$ system also provides a significant reduction in system complexity because the β measurement and all integrations are removed. The value of $K_{\dot{\beta}}$ was changed from 2.5 to 1.9 after the system was installed and validated in the simulator. The change was based on pilot opinion and engineering judgment. A value of K_p of 10 was chosen to provide the same steady state sideslip rate as the standard system. The units of K_p for the $\dot{\beta}$ configuration are deg/sec sideslip rate per inch of rudder pedal travel. This provides the pilot with the capability to command sideslip rate up to the $\pm 6°$ SAS rudder actuator limits. The units for K_p in the β-$\dot{\beta}$ system are degrees sideslip angle per inch of rudder travel again up to the $\pm 6°$ actuator limits. Figures 23a and 23b show a comparison of these three systems at a high dynamic pressure, Mach .9 at 10000 feet, and a low dynamic pressure,

Standard SAS

$\dot{\beta}$ SAS

β-$\dot{\beta}$ SAS
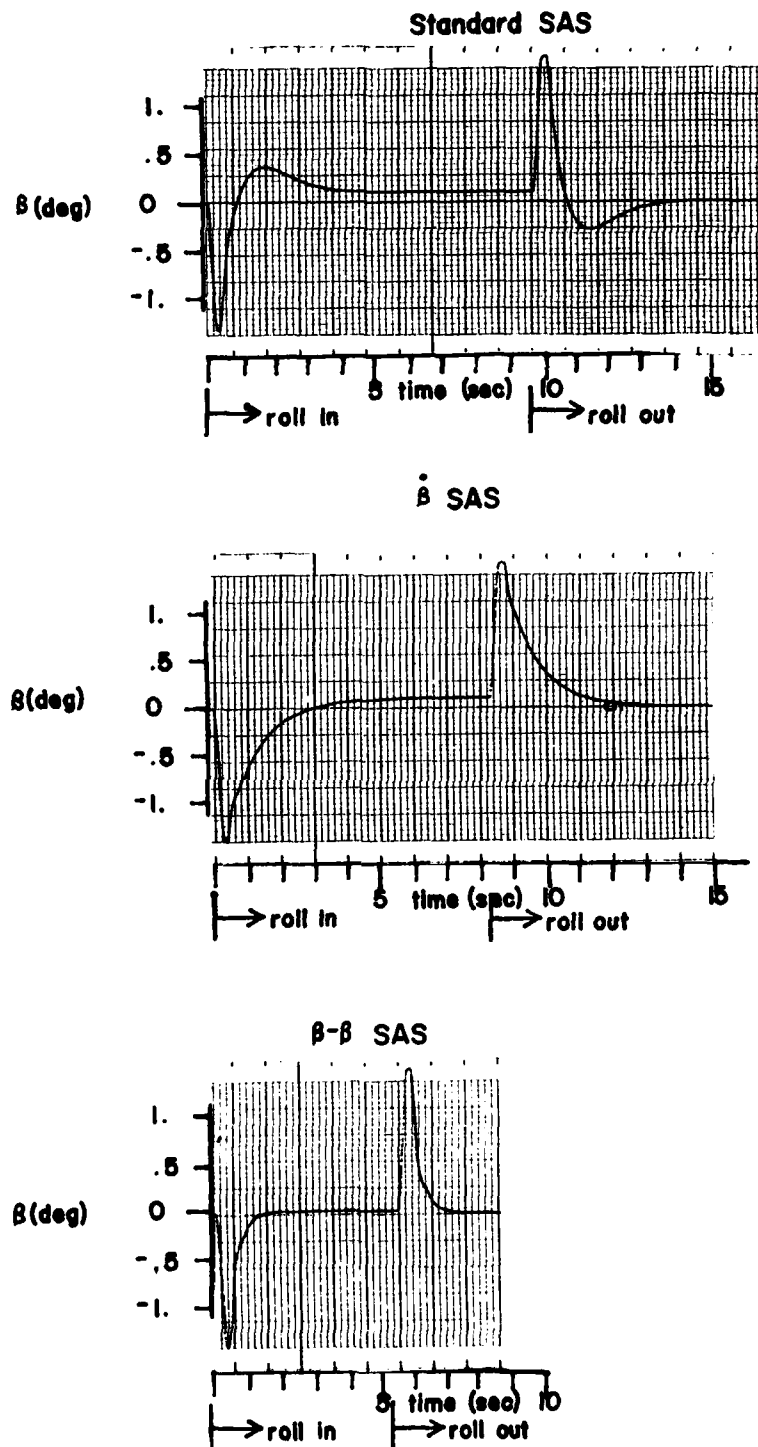
Figure 23a.   SAS Comparison at Mach .9, 10000 Feet
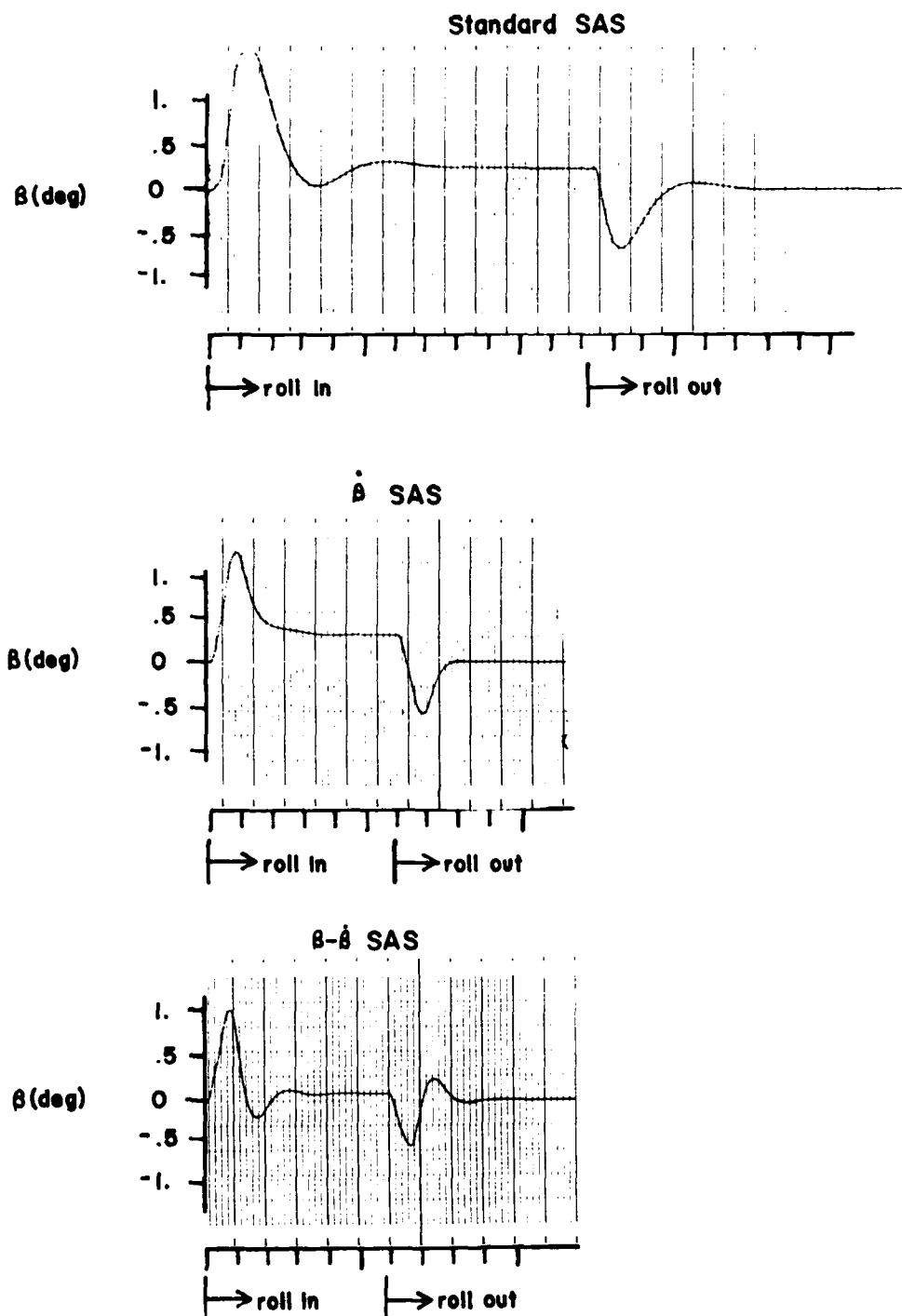
Figure 23b.   SAS Comparison at Mach .6, 30000 Feet

Mach .6 at 30000 feet. The responses to a 60° roll input followed by a rollout show that both the $\dot{\beta}$ and the β-$\dot{\beta}$ system eliminate the overshoot at high dynamic pressures and reduce maximum sideslip excursion at low dynamic pressure.

The experiment was set up using two pilots flying each of the three control systems four times. The pilots were flight test pilots experienced and current in the F-106. The task performed by the pilots was tracking a constant g target. The experiment was run at the following three flight conditions: Mach .72 at 10000 feet with 3 g target, Mach .9 at 10000 feet with 3 g target, and Mach .9 at 10000 feet with 6 g target. These flight conditions were chosen to provide realistic ATA tracking conditions. The tracking was performed using a fixed reticle depressed 50 milliradians from the waterline.

The experiment was designed specifically to measure the difficulty of the tracking task using the three SAS models and was set up similar to handling qualities during tracking (HQDT) tests, with some minor modifications. As in HQDT tests, the pilot's task was to keep the pipper superimposed on the target. Unlike normal HQDT tests, the pilots were allowed to use rudder pedals for aircraft control. This use of rudder pedals during tracking, not normally allowed in an HQDT test, was allowed because the pilots indicated that the rudder was the main lateral control used at large angles of attack. Initially the pilots were not told which system they were flying; this was done to avoid any biasing of the results. Later and for all the data runs, the pilots were informed of the system being flown. This was necessary because the pilots had developed different techniques for flying with each system.

Since the purpose of the new system is to improve lateral tracking, a quantitative measure of merit for this improvement was needed. This measure of merit was chosen to be the standard deviation of the tracking error. Since the system tested acts only on the lateral modes, the total error was divided into elevation and azimuth errors. The elevation and azimuth means are also included as an indicator of the actual point about which the pilot was tracking. To make the steady state tracking

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error statistics valid, the acquisition transients at the beginning of
each run were deleted. During this acquisition phase, the pilots often
generate large tracking errors while attempting to establish an in-plane
steady-state tracking turn behind the target. The errors are extremely
difficult to analyze quantitatively and are large relative to the steady
tracking errors; therefore, if included, they would have decreased the
usefulness of the standard deviation as a quantitative measure of merit.
In addition to these quantitative measures, the pilot opinions were
obtained in the form of pilot ratings based on the Cooper-Harper Scale
(Figure 24). These ratings, along with the means and standard deviations
of the tracking errors, provided the measures of merit for evaluating
the three SAS's.

2. SIMULATION RESULTS

Approximately 75 runs provided data which could be used for evaluating
the systems. Table 3 shows the results of these runs in terms of the
quantitative measures of merit described earlier. To eliminate the
acquisition transients, the middle 30 seconds of the 60-second runs
were used for calculating the error statistics for the 3 g runs. For the
6 g runs, the middle 20 seconds of the 45-second runs were used.

Although the mean tracking errors for three SAS's are shown, they
provide little insight into the relative merits of the different systems.
These mean values are more a function of pilot technique than of the
quality of the SAS. This is evident in the azimuth means where Table 3
shows pilot 1 to consistently track left of the target and pilot 2 to
consistently track right of the target. These different means could also
be due to the position of the pilot's head and his resulting view through
the HUD. The elevation means show that the pilots tracked consistently
below the target with large error magnitudes as g and airspeed increased
with little apparent relation to the SAS's. The elevation means could also
have been effected by bias in the data measurement system in the LAMARS
facility or again by the pilots' head location.

AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION	PILOT RATING
Excellent Highly desirable	• Pilot compensation not a factor for desired performance	1
Good Negligible deficiencies	• Pilot compensation not a factor for desired performance	2
Fair – Some mildly unpleasant deficiencies	• Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	• Desired performance requires moderate pilot compensation	4
Moderately objectionable deficiencies	• Adequate performance requires considerable pilot compensation	5
Very objectionable but tolerable deficiencies	• Adequate performance requires extensive pilot compensation	6
Major deficiencies	• Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question.	7
Major deficiencies	• Considerable pilot compensation is required for control	8
Major deficiencies	• Intense pilot compensation is required to retain control	9
Major deficiencies	• Control will be lost during some portion of required operation	10

ADEQUACY FOR SELECTED TASK OR REQUIRED OPERATION*

Is it Satisfactory without improvement?

Yes → No → Deficiencies warrant improvement

Is adequate performance attainable with a tolerable pilot workload?

Yes → No → Deficiencies require improvement

Is it controllable?

Yes → No → Improvement mandatory

Pilot decisions

*Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Figure 24. Cooper-Harper Rating Scale

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TABLE 3

SIMULATION RESULTS

M = .72, 3 g, 10000 FEET

Pilot 1

System	Azimuth Error Mean	SD	Elevation Error Mean	SD	Total Error SD
Standard	-4.54	11.18	-8.58	6.38	12.87
$\dot{\beta}$	-.47	6.28	-10.66	3.88	7.38
$\beta-\dot{\beta}$	-1.27	6.3	-9.1	3.25	7.09

M = .9, 3 g, 10000 FEET

System	Azimuth Error Mean	SD	Elevation Error Mean	SD	Total Error SD
Standard	-1.91	13.14	-9.79	3.93	13.72
$\dot{\beta}$	-1.9	9.08	-9.01	4.06	9.95
$\beta-\dot{\beta}$	1.71	12.11	-8.97	4.23	12.83

M = .9, 6 g, 10000 FEET

System	Azimuth Error Mean	SD	Elevation Error Mean	SD	Total Error SD
Standard	-3.75	15.02	-17.13	11.89	19.6
$\dot{\beta}$	-2.04	13.01	-18.71	11.34	17.26
$\beta-\dot{\beta}$	-1.75	18.72	-17.72	7.47	20.16

Pilot 2

M = .72, 3 g, 10000 FEET

System	Azimuth Error Mean	SD	Elevation Error Mean	SD	Total Error SD
Standard	2.21	12.58	-1.91	7.32	14.56
$\dot{\beta}$	2.82	9.43	-3.06	5.82	11.08
$\beta-\dot{\beta}$	2.99	9.88	-3.57	5.23	11.18

M = .9, 3 g, 10000 FEET

System	Azimuth Error Mean	SD	Elevation Error Mean	SD	Total Error SD
Standard	3.82	13.4	-5.52	5.71	14.57
$\dot{\beta}$	5.36	9.89	-4.47	4.15	10.73
$\beta-\dot{\beta}$	.92	15.94	-3.74	4.71	16.62

M = .9, 6 g, 10000 FEET

System	Azimuth Error Mean	SD	Elevation Error Mean	SD	Total Error SD
Standard	1.73	17.41	-10.95	12.79	21.6
$\dot{\beta}$	5.48	17.08	-7.55	10.59	20.1
$\beta-\dot{\beta}$	8.87	21.54	-8.55	12.67	25

The most important quantitative measure of merit is the standard
deviation of the tracking errors. The standard deviation shows the
precision with which the pilot can hold the pipper on the target. The
smaller the standard deviation, the more precisely the pilot can hold
the pipper on the target.

To determine the statistical significance of the SAS effects on
the results, a three-way analysis of variance was performed on azimuth,
elevation, and total error (vector sum of azimuth and elevation error).
The analysis is shown in Appendix E. The three error sources were SAS,
pilot, and flight condition. The results are shown in Table 4 (a through c)
in terms of level of significance for the different error sources. These
levels of significance describe the probability of mistakenly attributing
changes in tracking error to one of the error sources when in fact that
error source was not the factor causing the change. For instance, the
.0173 level of significance of the SAS as an error source in azimuth
error means that there is a .0173 probability that the changes, which
occurred in azimuth tracking error when the SAS was changed, were not
due to the SAS at all but were either random errors or due to some other
factor. The results show that the SAS was indeed significant as an
error source. The results also show that the pilot and flight condition
were even more significant as error sources.

Since the analysis of variance shows the SAS effects to be signi-
ficant, the results from Table 3 can be examined in more detail. The
percentage improvement over the standard SAS, in terms of standard
deviation of the tracking error, is shown in Table 5. There are quite
large improvements at Mach .72, 10000 feet but as the Mach number and
g loading increase, the levels of improvement become smaller. This
decrease in percentage improvement is probably due to the increasing
difficulty of the task itself, which tends to overwhelm and mask the
SAS differences. This is also evident in the analysis of variance,
which shows the flight condition to have a highly significant effect
on the results. Pilot skill also appears to be important to the results.
Pilot 1 consistently had smaller tracking errors and also had consistently
higher levels of improvement. As with flight condition, this pilot

TABLE 4

ANALYSIS OF VARIANCE RESULTS

Error Source	Level of Significance
Pilot	.0163
Flt Cond	.00003
SAS	.0173

a. Azimuth Error

Error Source	Level of Significance
Pilot	.0201
Flt Cond	.00001
SAS	.044

b. Elevation Error

Error Source	Level of Significance
Pilot	.0053
Flt Cond	.00001
SAS	.0135

c. Total Error

TABLE 5

PERCENT IMPROVEMENTS OVER STANDARD SAS*

M = .72, 3 g, 10000 FEET

	Pilot 1			Pilot 2		
System	Azimuth Error	Elevation Error	Total Error	Azimuth Error	Elevation Error	Total Error
$\dot{\beta}$	44	39	43	25	20	24
$\beta-\dot{\beta}$	44	49	45	21	29	23

M = .9, 3 g, 10000 FEET

$\dot{\beta}$	31	-3	27	26	27	26
$\beta-\dot{\beta}$	8	-8	6	-19	18	-14

M = .9, 6 g, 10000 FEET

$\dot{\beta}$	13	5	10	2	17	7
$\beta-\dot{\beta}$	-25	37	-5	-24	1	-16

*Negative value indicates a degradation

effect was evident in the analysis of variance. Based on the quantitative measures of merit in Tables 3 and 5, the $\dot{\beta}$ SAS appears to be best, followed by the standard SAS and the $\beta-\dot{\beta}$ SAS.

The three SAS's were also compared qualitatively using the Cooper-Harper rating scale. These ratings, for the 3 g runs, are shown in Table 6. These qualitative measures follow very closely the quantitative measures of Tables 3 and 5. They show the $\dot{\beta}$ system to be best followed by the standard and the $\beta-\dot{\beta}$ system. Figures 25a-25c show representative pipper traces at the Mach .9, 3 g flight condition using each of the three SAS's. These pipper traces are from runs flown by pilot 1. The improvement is evident in the $\dot{\beta}$ SAS, Figure 25c. Figure 26 also shows the improvement provided by the $\dot{\beta}$ SAS. In Figure 26, the standard SAS was being flown by the pilot as he tracked a 3 g target; at the point shown, the standard SAS was turned off and the $\dot{\beta}$ SAS turned on. The improvement is evidenced by the elimination of the low frequency oscillation.

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TABLE 6

COOPER-HARPER RATINGS (3 g ENCOUNTERS)

System	Pilot 1	Pilot 2
Standard	3	4
$\dot{\beta}$	2	3
β-$\dot{\beta}$	5	5

Although the nonpiloted simulations indicated that the β $\dot{\beta}$ system was better than the $\dot{\beta}$ system, in terms of dynamic response, the pilots preferred and performed better with the $\dot{\beta}$ system, a rate control. This apparent discrepancy can probably be attributed to the fact that the pilots were most familiar with rate control, as with the standard SAS; the position control of the β-$\dot{\beta}$ system was therefore, something new which the pilots had to learn how to use as they evaluated it. This lack of experience in using position control of sideslip might have put a bias on the results. Unfortunately, this possible bias cannot be measured using the data and should not, therefore, enter the results.

In summary, the LAMARS simulation showed that the $\dot{\beta}$ SAS provides a significant improvement over the standard SAS. This improvement was evidenced by both quantitative measures of merit, tracking error, and qualitative measures of merit, pilot ratings.
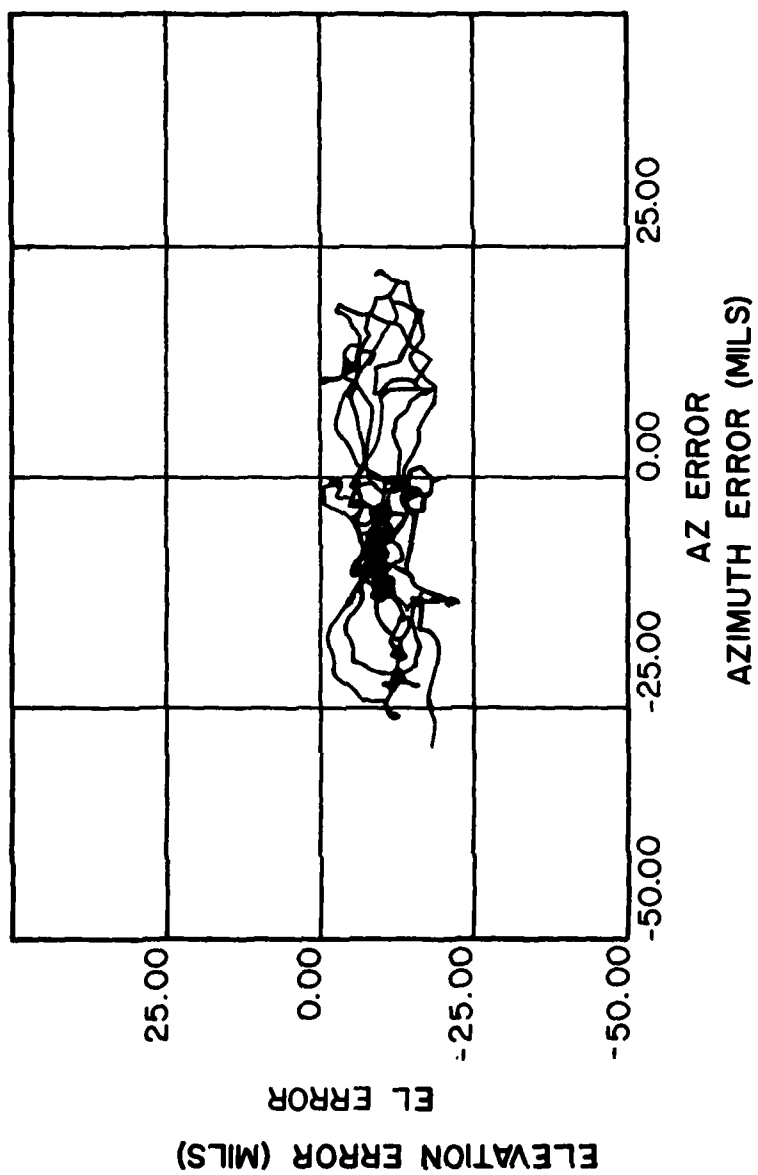
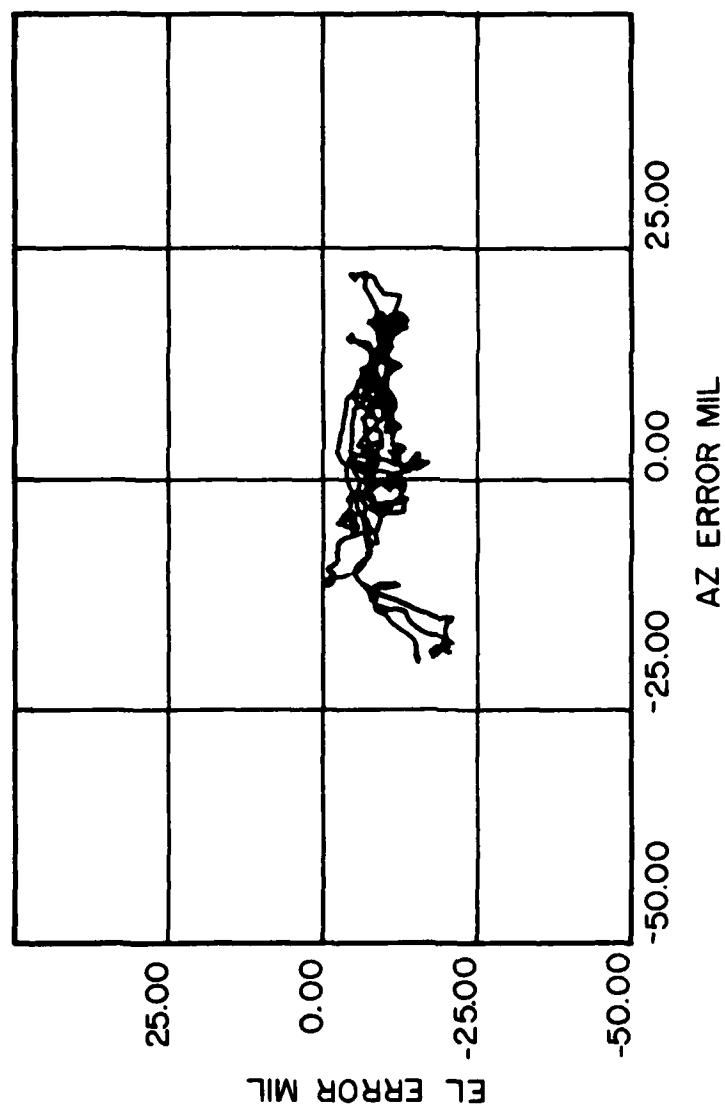Figure 25a. Standard SAS Pipper Trace at Mach .9, 10000 Feet, 3 g

Figure 25b. β-β̇ SAS Pipper Trace at Mach .9, 10000 Feet, 3 g

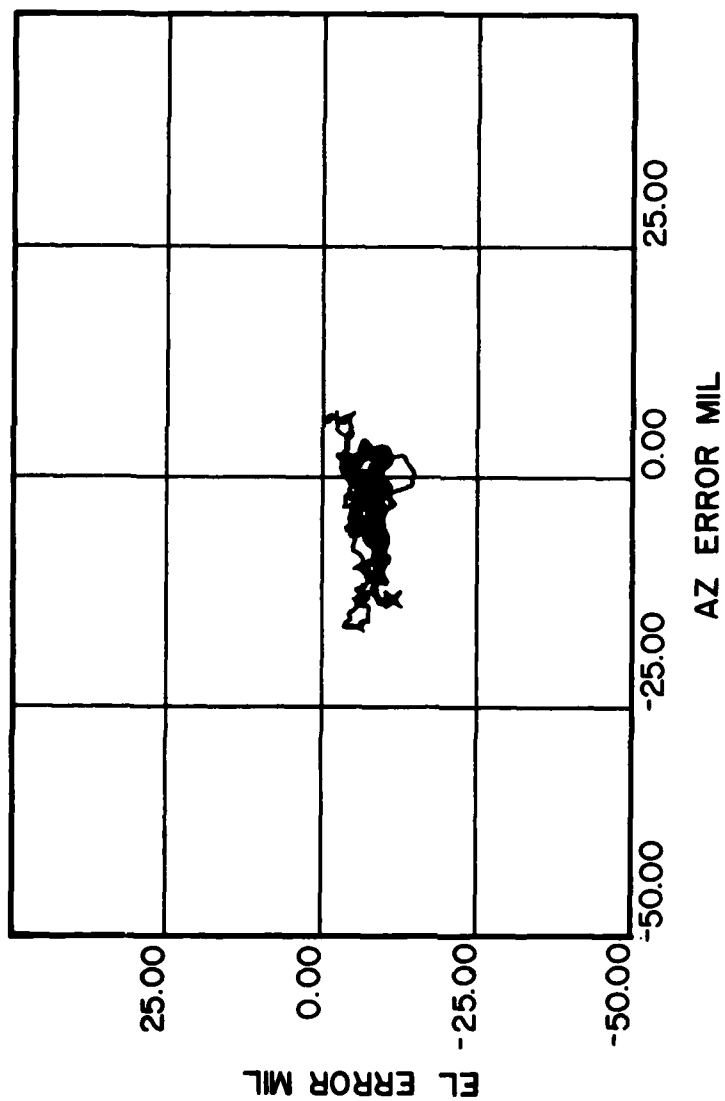Figure 25c. β̇ SAS Pipper Trace at Mach .9, 10000 Feet, 3 g
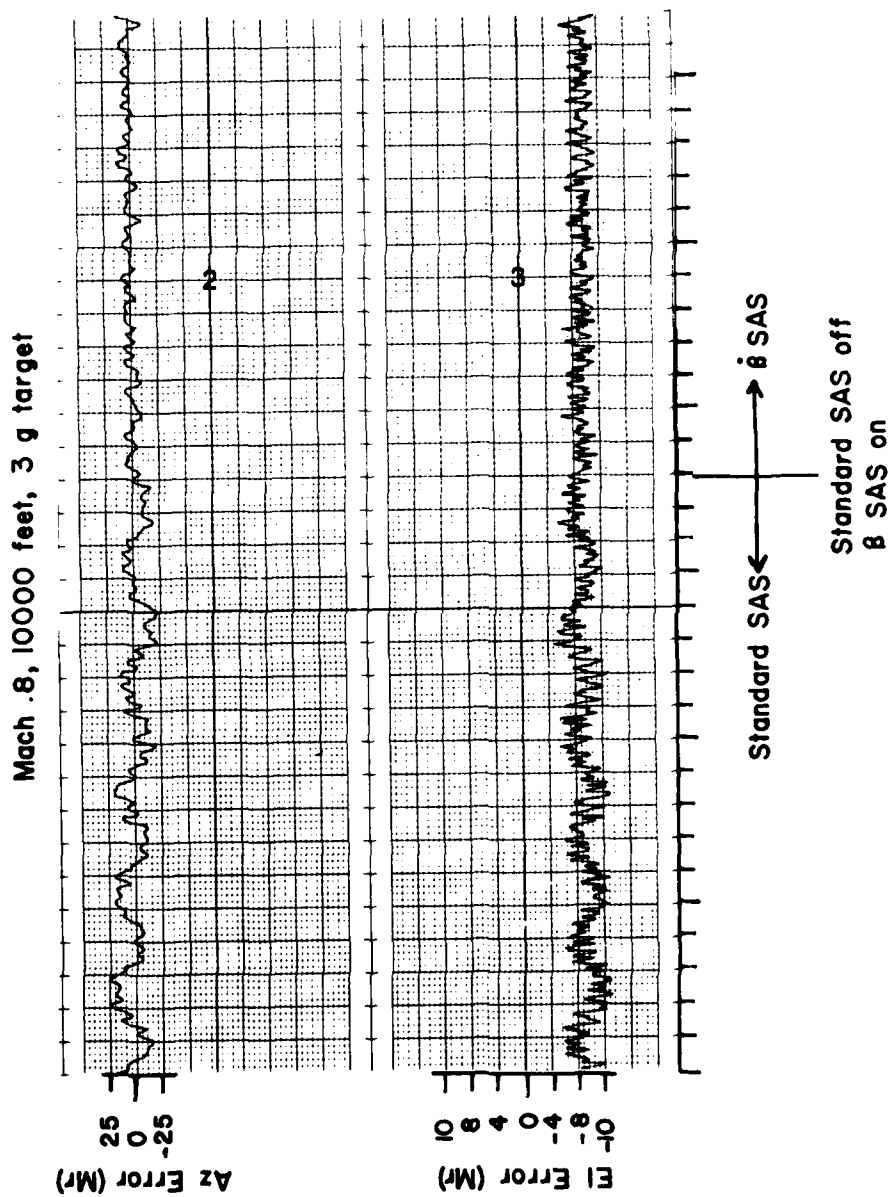
Figure 26. Tracking Error Reduction with β̇ SAS

SECTION V

F-106 FLIGHT TEST

1. SYSTEM CONFIGURATION AND IMPLEMENTATION

Based on the results of the piloted simulation, both analysis results and pilot comments, the Aerospace Defense Command (ADCOM/DOV) gave the Flight Dynamics Laboratory approval to flight test the modified SAS on an F-106 at Tyndall AFB, Florida. The Flight Dynamics Laboratory, with assistance from the 475th Test Squadron from Tyndall AFB, designed a flight test implementation which allowed for much flexibility during the flight test. The Class II modification package based on this design was approved by Air Force Systems Command. The design for flight test included only provisions to evaluate the sideslip rate ($\dot{\beta}$) feedback. The reasons for looking at only the $\dot{\beta}$ feedback are twofold. Primarily, the pilot comments and performance measures from the piloted simulation shows this system to have a much greater performance improvement potential than the β-$\dot{\beta}$ system. Also, the cost for implementing the $\dot{\beta}$ system was considerably less because no integrations were required in the control law.

During the design of the flight test implementation, the Flight Dynamics Laboratory presented an option to ADCOM which would allow for the addition of a roll SAS to the F-106 being tested. The reasons for including this option were that the F-106 did not have roll rate feedback to the SAS, the pilot controlled the elevon position directly, and the change would be very simple, involving only a circuit change to the existing control system. ADCOM/DOV approved this addition to the flight test, and the roll SAS design was included and approved in the Class II modification package.

The F-106 avionics system and flight control system were well suited for testing the $\dot{\beta}$ SAS and roll SAS because they required only minor modifications to the existing system. The Hughes-built IRAM computer was used for all SAS calculations, both yaw and roll. Since the IRAM computer is part of the MA-1 fire control and automatic intercept system, existing electrical paths from the IRAM computer to

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the 464821 flight control interface box were used to carry the calculated
SAS commands to the flight control system actuators. Figure 27 shows a
conceptual block diagram of the system implementation.

The standard yaw SAS is a single-thread analog system located in the
821 unit. The sensor outputs from the turn rate transmitter (TRT), yaw
rate and roll rate, are input to this 821 unit which does the analog
SAS calculation for roll and pitch and then sent to the rudder actuator
and the two elevon actuators.

The rudder actuator mechanically limits the SAS command rudder
movement to $\pm 6°$. Likewise, the pitch SAS commands are mechanically
limited to $\pm 1°$ by the elevon actuators. This pitch authority ($\pm 1°$) was
also the limit for the roll SAS since the roll SAS consisted of using
the existing pitch system but in a differential manner.

The $\dot{\beta}$ SAS implementation is shown in Figure 28. Figure 29 further
describes the inputs and switching used in the $\dot{\beta}$ SAS. To have all the
quantities necessary to solve the $\dot{\beta}$ equation in the MA-1 IRAM computer,
some standard inputs to the computer had to be removed and replaced with
sensor measurements needed by the $\dot{\beta}$ SAS. The pitch rate normally input
to the computer was replaced by an angle of attack (α) signal from an α
vane located on the pitot-static boom. The lateral acceleration (A_y),
which came from a Honeywell inertial reference platform (IRP), replaced
the existing gunsight sideslip measurement. Rudder pedal position (δ_{rp})
replaced the right elevon position. These three signals, α, A_y, and δ_{rp},
were available from instrumentation installed previously for an F-106
parameter identification flight test.

The roll SAS implementation was set up in the same way as the $\dot{\beta}$ SAS.
Figures 30 and 31 show the implementation and switching logic used for
the roll SAS. The lateral stick position needed by the roll control law
is taken from a lateral stick position potentiometer and input to the
computer in the location normally containing left elevon position.

The computer program was set up to enable a maximum amount of flexi-
bility in both system checkout and flight test validation. The program
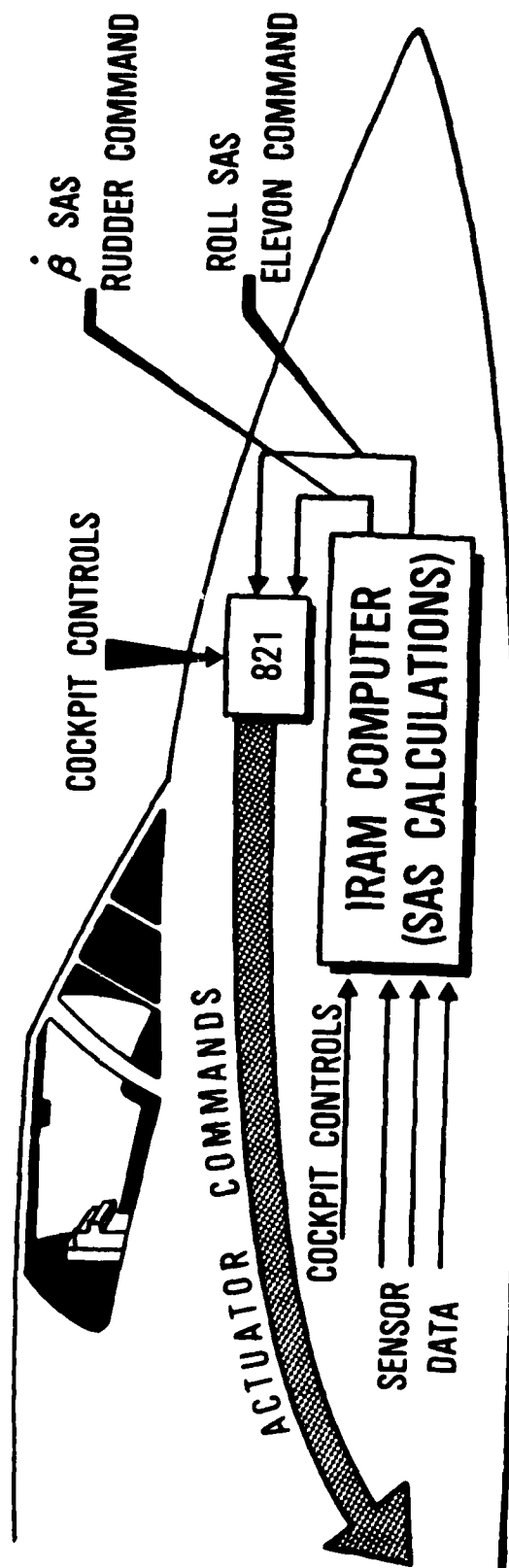had an option for a ground check by using the aircraft short system
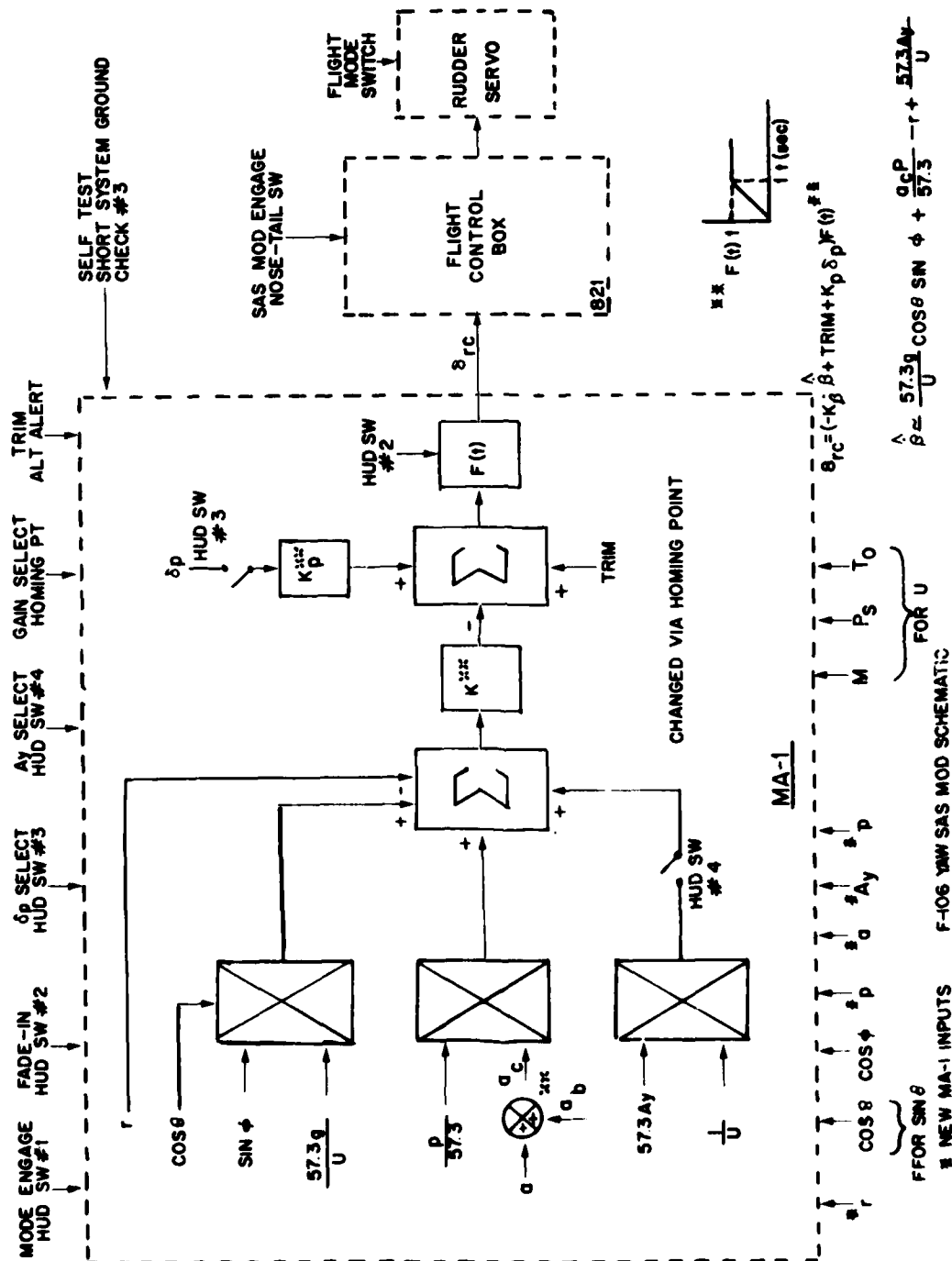
Figure 27. F-106 SAS Conceptual Block Diagram

Figure 28. $\dot{\beta}$ SAS Implementation

$$\delta_{rc} = (-K_{\dot\beta}\,\dot{\hat\beta} + \text{TRIM} + K_p\delta_p)F(t)^{\#\#}$$

$$\dot{\hat\beta} \simeq \frac{57.3g}{U}\cos\theta\sin\phi + \frac{q_c p}{57.3} - r + \frac{57.3 A_y}{U}$$

$$\delta_{rc} = (K_p \delta_p + TRIM - K_{\dot{\beta}} \hat{\dot{\beta}}) F(t)$$

where $\hat{\dot{\beta}} = \dfrac{[p(\alpha + \alpha_b) - r + 57.3 \dfrac{K_A A_y}{U} + 57.3 \dfrac{g}{U} \cos\theta \sin\phi]}{57.3}$

$g = 32.2 \text{ ft/sec}^2$

COMPUTER OUTPUT

	OUTPUT LOCATION	SCALING	RANGE
δ_{rc}	LH Elevon Command (deg)	8.33 V/deg	0-100V, ±6°

Computer Inputs (Variables)

	Source	Input Location	Scaling	Range
p (roll rate, deg/sec)	TRT	existing (E18a)	10 deg/sec/V	±5V
α (angle of attack, deg)	boom	pitch rate (E25)	9 deg/volt	±5V, ±45°
r (yaw rate, deg/sec)	TRT	existing (E16a)	4 deg/sec/V	∓5V
A_y (lateral acceleration, ft/sec)	Honeywell IRP	gunsight δ (E26)	212 ft/sec/volt	±4.025V, ±800 ft/sec
u (airspeed, ft/sec)	existing	existing		
sin θ (cos θ calculated from sin θ)	existing	existing		
sin φ (roll angle)	existing	existing		
δ_p (rudder pedal position, in)	rudder pot	RT elevon position(A22)		50V±30V,±3.25 in
TRIM (System electrical trim, deg)	Altitude warning	existing		±6°

(Variable gains)

α_b (angle of attack, bias deg)

$K_{\dot{\beta}}$ (β gain, deg/deg/sec)
K_p (pilot rudder pedal position gain, deg/in)

These variable gains are set using the Homing Point Selector as a logic indicator to set these gains as shown in Table 1.

(Discretes)

	Function
HUD Switch =1	Betadot Mode Select
HUD Switch =2	Fade-in and Fade-out control for SAS via F(t)
HUD Switch =3	Selects δ_p: ON K_p = values in Table 1; OFF K_p = 0
HUD Switch =4	Selects A_y: ON K_A = 1; OFF K_A = 0

$F(t)$ vs time (sec), with $F(t)$ axis reaching 1, and 1 time (sec) shown.
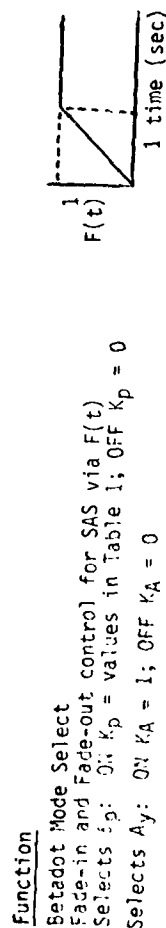
Figure 29. $\dot{\beta}$ SAS Inputs and Switching Logic

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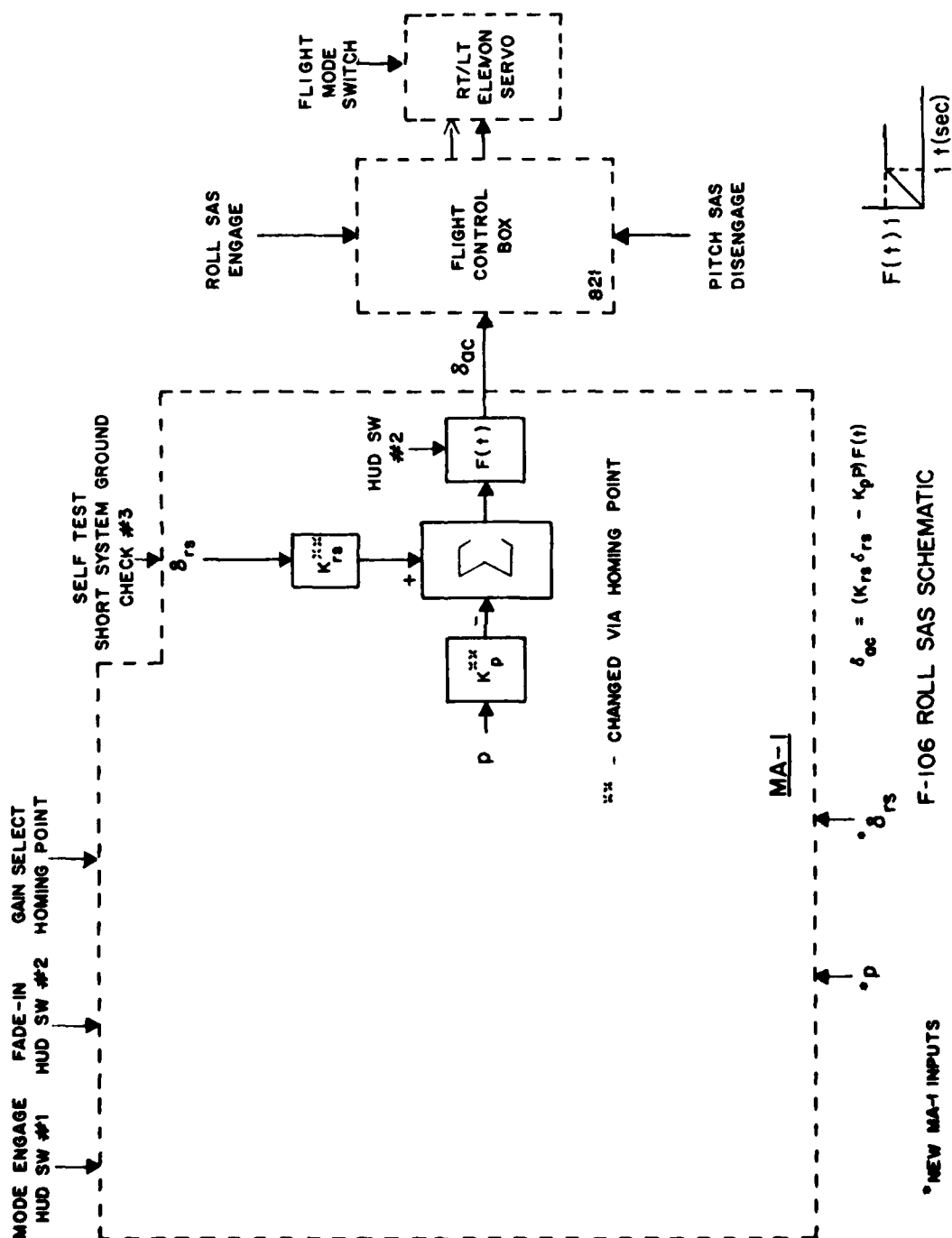
Figure 30. Roll SAS Implementation

$$\delta_{ac} = (K_s\delta_{ps} - K_{rr}P)F(t)$$

COMPUTER OUTPUT	OUTPUT LOCATION	SCALING	RANGE
δ_{ac}	RH Elevon Command (deg)	50 V/deg	0-100V, ±1°

COMPUTER INPUTS	SOURCE	INPUT LOCATION	SCALING	RANGE
(Variables)				
P (roll rate, deg/sec)	IRP	existing (E25)	10.0 deg/sec/V	±5V
δ_{ps} (lateral stick position, in)	stick potentiometer	LH Elevon Position (A21)	50±30V	±3.5 in
(Variable gains)				
K_s (stick gain, deg/in		These gains will be set using the Homing Point Indicator as a		
K_{rr} (roll rate gain, deg/deg/sec)		logic indicator to set these gains as shown in Table 1.		

(Discretes)	Function
HUD Switch #1	Selects roll SAS mode
HUD Switch #2	Fades in and out control law via F(t)
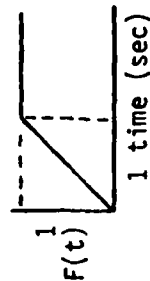
Figure 31. Roll SAS Inputs and Switching Logic

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ground check number three (SSGC #3). When SSGC was engaged, the computer would read stored data locations instead of the sensor input. The control law was computed using these values for the sensor measurements. The resulting rudder deflection was then compared with the rudder deflection which should theoretically have occurred. These ground check calculations are shown in Figure 32.

Flight test flexibility was achieved by designing the system with variable gains and SAS mode switching logic. To achieve variable gains in the control law itself, the homing point selector (an existing navigation control) was used as a gain select. For each switch location on the homing point select, a different set of gains were used in the SAS calculations. Table 7 shows the homing point values and the associated gains. In addition to the variable gains, adjusted by the homing point select, an electrical bias or trim was available using the altitude alert switch, an existing digital input to the computer. This electrical bias allowed the pilot to trim out the bias resulting from an accumulation of sensor biases. This electrical trim was used in place of the normal trim because the normal rudder trim uses part of the $\pm6°$ SAS authority of rudder actuator. By using the electrical trim, the SAS control law still had even $\pm6°$ authority instead of an uneven authority such as $+5°$, $-7°$ which could occur if a $1°$ bias was eliminated using the standard rudder trim.

TABLE 7

HOMING POINT SELECT GAIN VALUES

HD	$K_{\dot{\beta}}$	K_p	α_b	K_{rr}	K_s
A	1.9	5	4	.15	3
B	1.9	5	1	.15	3
C	1.25	3.28	4	.15	3
D	2.25	5	4	.15	3
E	1.5	3.45	4	.15	3
F	1.9	5	3	.15	3
G	1.9	5	6.36	.15	3
H	1.9	2.5	4	.15	3
I	1.9	10	4	.25	3
J	1.9	5	2	.15	3
K	1.9	5	4	.15	2
L	1.9	5	4	.15	4
M	1.9	5	4	.1	3
N	1.9	5	4	.2	3

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Rudder Check

$$\delta_{rc} = (K_p \delta_p + TRIM - K_{\dot{\beta}} \hat{\dot{\beta}})$$

$$\hat{\dot{\beta}} = \frac{p(\alpha + \alpha_b)}{57.3} - r + \frac{57.3 A_y}{U} + \frac{57.3 g \cos\theta \sin\phi}{U}$$

$p = 5$ deg/sec $\theta = -5°$

$\alpha = 7$ deg $\phi = -15°$

$r = 5$ deg/sec $TRIM = 0$

$A_y = -3$ ft/sec^2 $\delta_p = -1.25$ in

$U = 862$ ft/sec^1

$$\hat{\dot{\beta}} = \frac{5(7 + \alpha_b)}{57.3} - 5 + \frac{57.3(-3)}{862} + \frac{57.3(32.2) \cos(-5°) \sin(-15°)}{862}$$

$$= .611 + .0873\alpha_b - 5 - .199 - .552$$

$$= .0873\alpha_b - 5.14$$

$$\delta_{rc} = [K_p * 1.25 + 0 - K_{\dot{\beta}} (.0873\alpha_b - 5.14)]$$

$$= -1.25 K_p - K_{\dot{\beta}} (.0873\alpha_b - 5.14)$$

Aileron Check

$$\delta_{ac} = (K_g \delta_{ps} - K_{rr} p)$$

$p = 5$ deg/sec

$\delta_{ps} = 0$

$$\delta_{ac} = 0 K_g - 5 K_{rr}$$

$$= -5 K_{rr}$$

Figure 32.   Built-in-Test

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The switching logic also allowed some of the parameters in the $\overset{\bullet}{\beta}$ SAS control law to be deleted from the control law calculation. Specifically, the heads up display (HUD) switches 3 and 4 were used to delete pilot rudder pedal position (δ_{rp}) and lateral acceleration (A_y) respectively. These options proved very helpful, both in debugging the system and in picking the best overall system configuration. HUD switch 1 was used to start the computer calculations and HUD switch 2 was used to fade-in the control law. The fade-in consisted of a 1-second ramp from zero to one. This fade-in is shown as F(t) on Figures 28-31.

The actual computer program which did the SAS calculations is shown in Appendix F. This IRAM assembly code shown did the $\overset{\bullet}{\beta}$ and roll SAS calculations, the rudder trim, gain changes, and also displayed a fixed reticle depressed 50 mils from the water line and 15 mils right of centerline. The cross was placed off center so that the vision splitter on the 106 did not interfere with the HUD camera. The computer program is located on the magnetic memory drum at the same location as the gunsight program; therefore, to load the program, the pilot selected Special Weapons (SPL WPM) on the weapon control panel.

2. FLIGHT TEST RESULTS

After several system checkout flights, the system was debugged and data flights were flown. The 475th Test Squadron flew the $\overset{\bullet}{\beta}$ and roll SAS during the months of June, July, and August of 1978. The system was flown by three different pilots during this period. Both basic handling qualities tests and handling qualities during tracking (HQDT) tests were flown by all three pilots.

The roll SAS proved to be the least effective of the two systems tested. This ineffectiveness was due primarily to limitations in the way the system was implemented. Since the roll SAS had only ±1 degree of elevon authority, small biases in roll rate and lateral stick position measurements saturated the system. This saturation meant that the control law would operate only in one direction. In spite of these limitations, the pilots felt that when the system was operating properly, it was very effective and desirable for air-to-air tracking. Unfortunately, the

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stick position and roll rate biases were present during most of the
flights, thereby making the roll SAS, on the whole, ineffective.
Additionally, instrumentation problems precluded the reduction of
aircraft data for the roll SAS flights.

The $\dot{\beta}$ SAS was shown to be effective in the ATA tracking task by
reductions in the tracking error shown on gun camera film. The lateral
acceleration (A_y) term in the $\dot{\beta}$ control law was switched out during the
data gathering flights because it was very noisy and added no real
improvement to the response. The system also showed to be an improvement
over the standard SAS in terms of reduction in pilot workload. These
conclusions are based primarily on pilot comments and on gun camera
film taken during many of the tracking encounters. There is also some
strip chart data of aircraft parameters which aided somewhat in system
evaluation. Unfortunately, the parameters most critical to the $\dot{\beta}$ system
evaluation, β and r, were not measured during the tests due to instrumen-
tation problems.

Figures 33 and 34 show a direct comparison between the standard SAS
and the $\dot{\beta}$ SAS with Homing Point E gains ($K_{\dot{\beta}}=1.5$, $K_p=3.45$). The long
straight line in the pipper trace of Figure 33 is caused by a data dropout
in the instrumentation system. The flight condition was Mach = .8,
10,000 ft. These figures show tracking error data during an aileron
reversal. In this case, the difficulty of the task masked much of the
SAS differences, although one can see a higher frequency content in the
$\dot{\beta}$ SAS error time plots. This higher frequency content is indicative of
the faster response available when the aircraft was flying with the $\dot{\beta}$
SAS engaged. Pilot comments confirmed the faster response time with the
$\dot{\beta}$ SAS. They also indicated this faster response to be a desirable
capability during ATA tracking.

Figures 35 and 36 show similar tracking error comparisons between
the standard SAS and the $\dot{\beta}$ SAS. Both a right and left 4 g turn at Mach .8
and 10,000 feet are shown. The right turn shows little difference
between the two systems other than the decreased response time of $\dot{\beta}$ SAS
as indicated qualitatively by the higher frequency content of the error
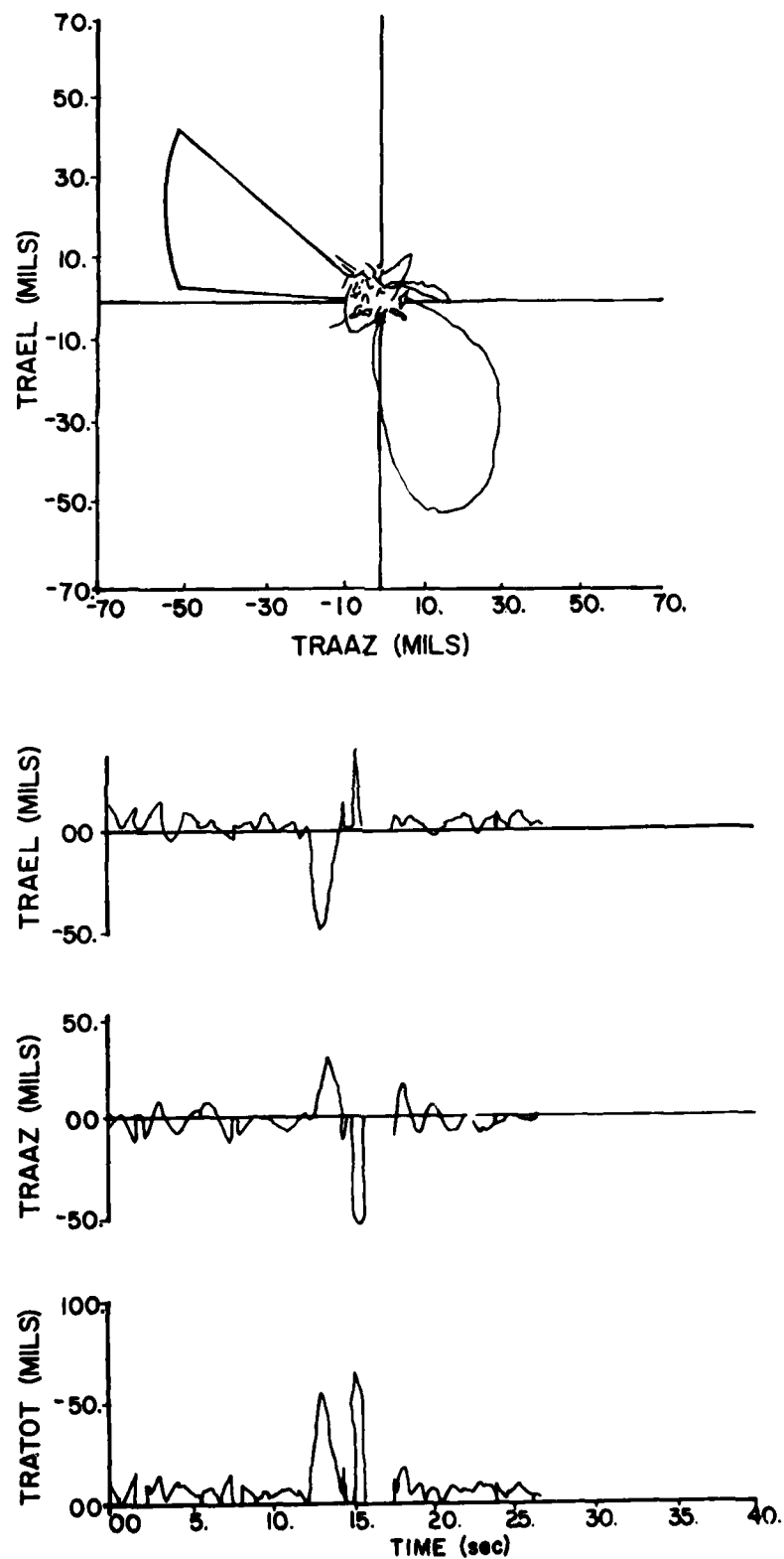
Figure 33.   Standard SAS, Aileron Reversal, Mach .8, 10000 Feet
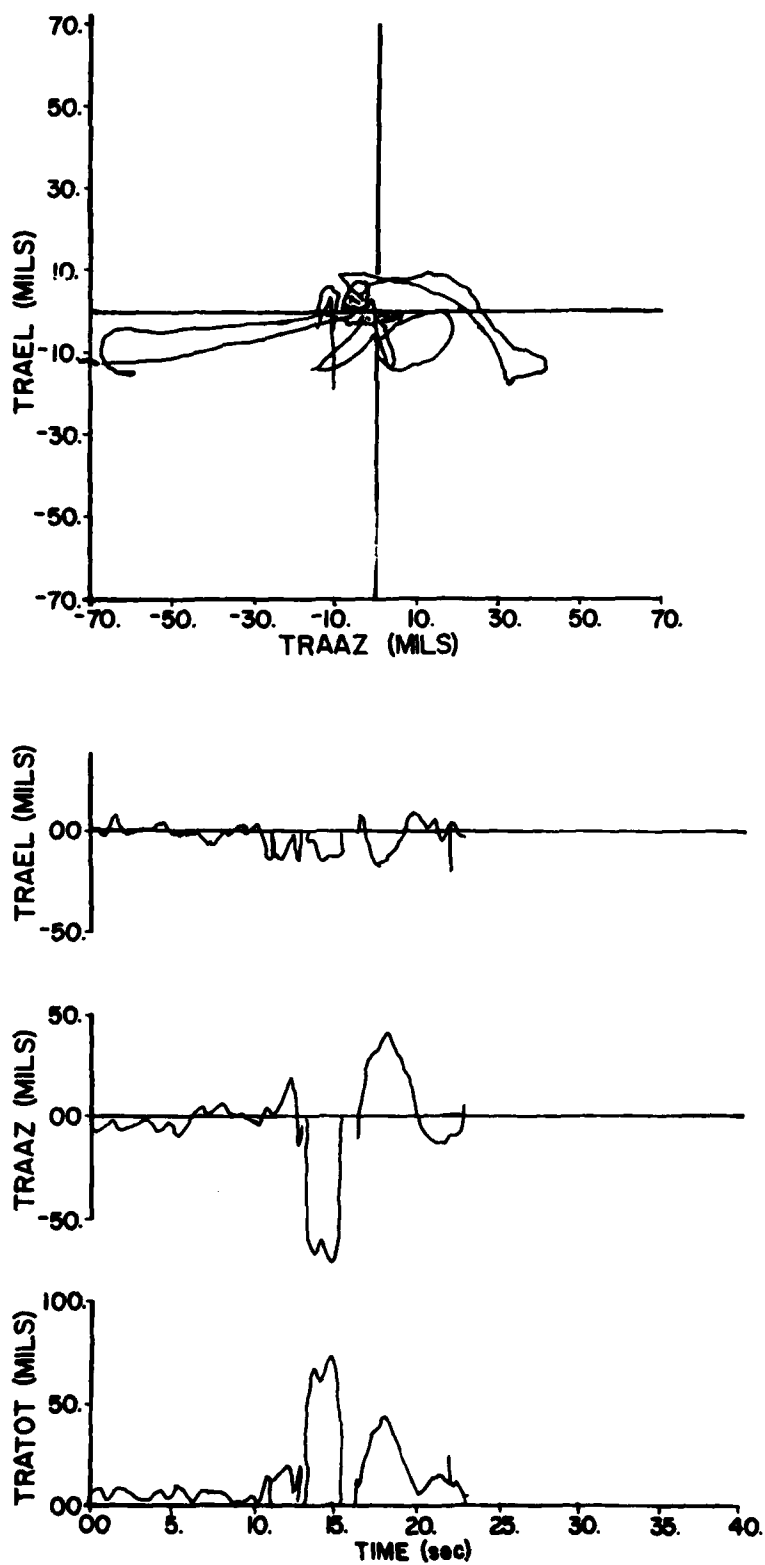
Figure 34. $K_{\dot{\beta}}$= 1.5, K_p=3.45, Aileron Reversal, Mach .8, 10000 Feet
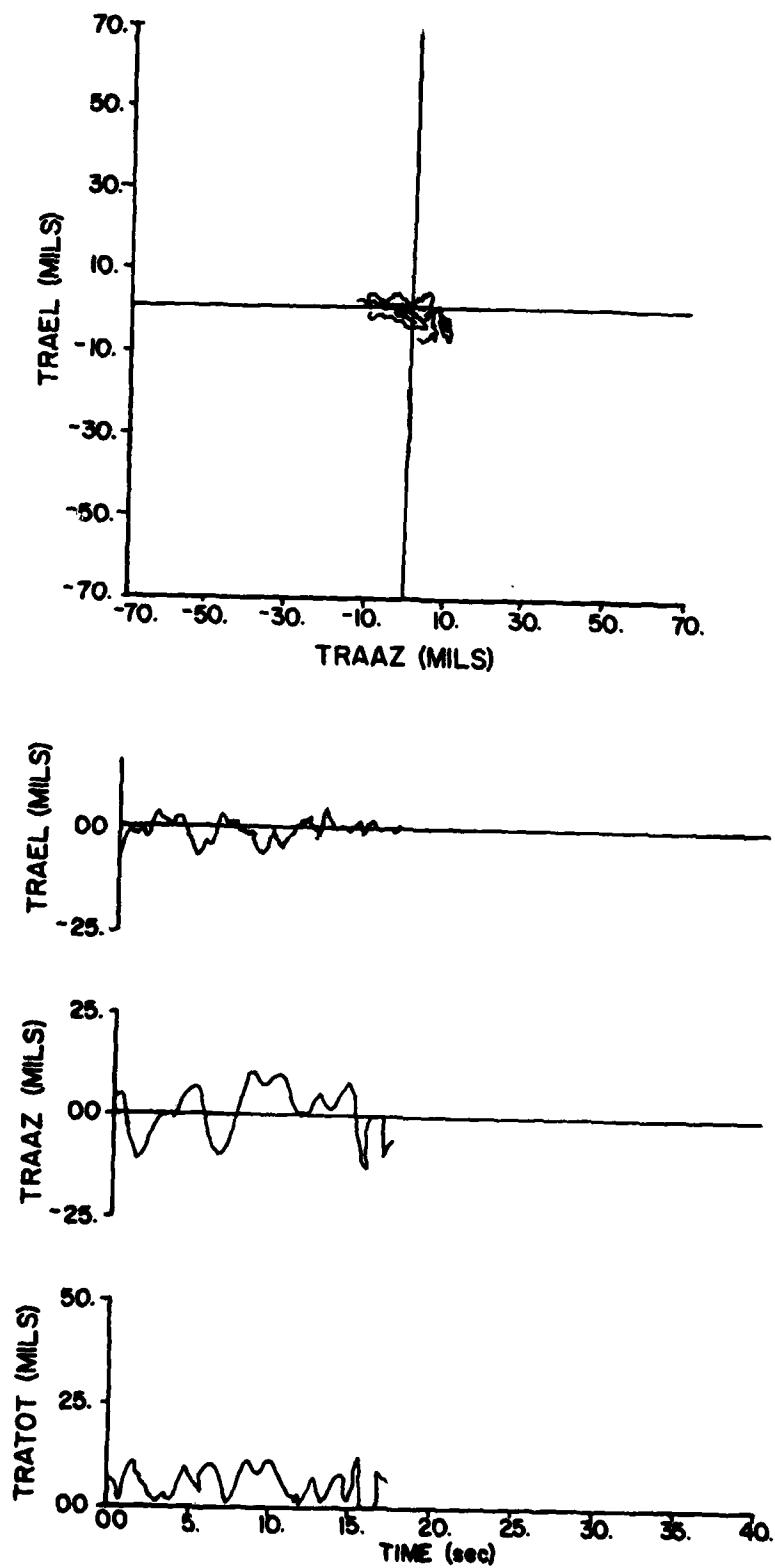
Figure 35.   Standard SAS, 4 g Turn, Mach .8, 10000 Feet
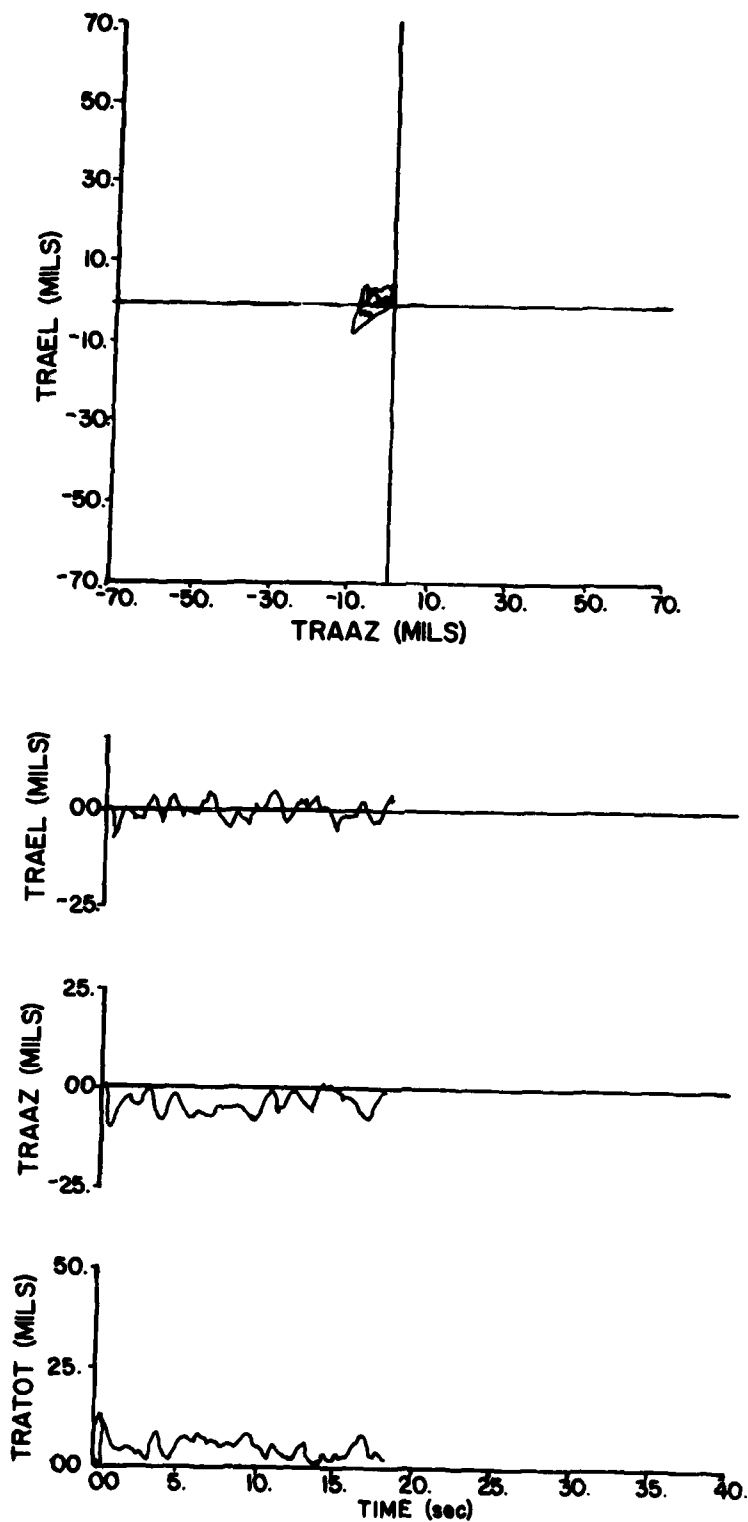
Figure 36. K_β°= 1.5, K_p=3.45, 4 g Turn, Mach .8, 10000 Feet

time plots. The left turn, however, does show a significant decrease in tracking error on both the pipper plot and the error time plots.

Figures 37 through 42 show additional flight test results for constant 3.5 to 4 g turns. The standard SAS results, Figure 37, show a fairly large pipper trace with excursions as high as ± 25 mils in both elevation and traverse. The $\dot{\beta}$ SAS, Figures 38 through 42, shows significant reduction in this aim wander. The results are especially impressive in Figure 38 with $K_{\dot{\beta}}=1.9$ and $K_p=3.45$, over 50% reduction in aim wander. Although these plots represent tracking performance for only one flight, they are representative of the performance achieved by all the pilots on all the test missions.

In addition to the improvement evidenced by the pipper plots, Figure 43 shows data which is indicative of the reduction in pilot workloads achieved using the system. The time history strip chart recordings from this figure were taken from the pass whose pipper plot is shown in Figure 42. The reduction in pilot workload is evidenced by the reduction in magnitude of the stick and rudder deflections. The decreased response time is evidenced by the higher frequency content of the control movements using the $\dot{\beta}$ SAS. The workload reduction evidenced by Figure 43 is very similar to the workload reduction evidenced by Figure 28 showing simulator results.

A total of three different pilots flew the modified SAS. The roll SAS did not function and was therefore not evaluated. All agreed that the $\dot{\beta}$ SAS was an improvement over the standard SAS during ATA tracking. The pilot comments indicated that the improvement in tracking capability was due to the "crisper", faster response available using the $\dot{\beta}$ SAS. The consensus was that the gains of $K_{\dot{\beta}}=1.9$ and $K_p=2.5$ were the best of those tested. The pilots felt that these gains made the best system by providing a quick but controllable response.
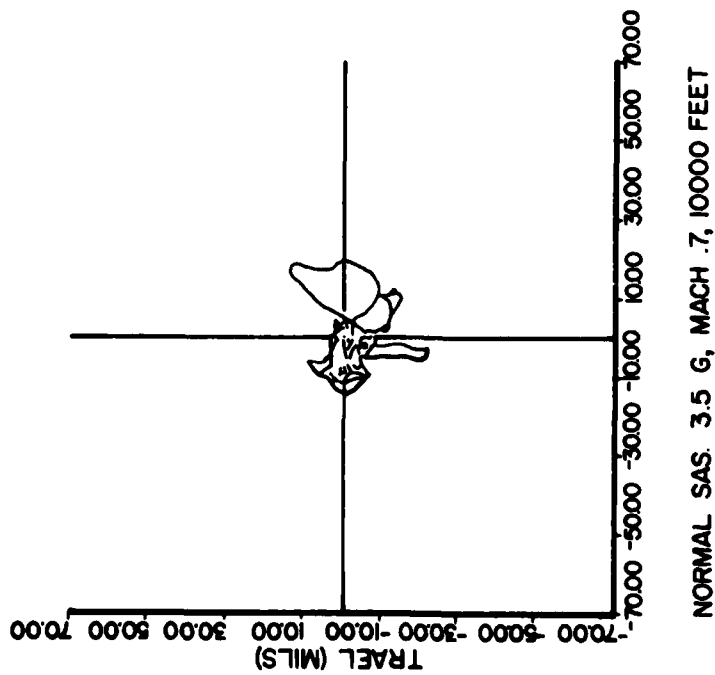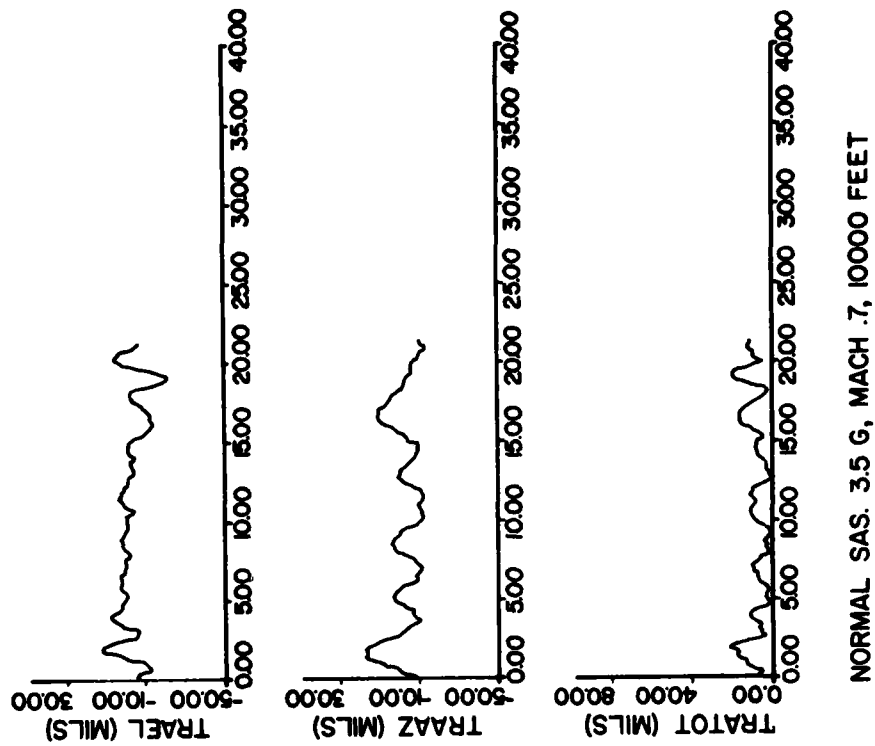
Figure 37.   Standard SAS, 3.5 g, Mach .7, 10000 Feet
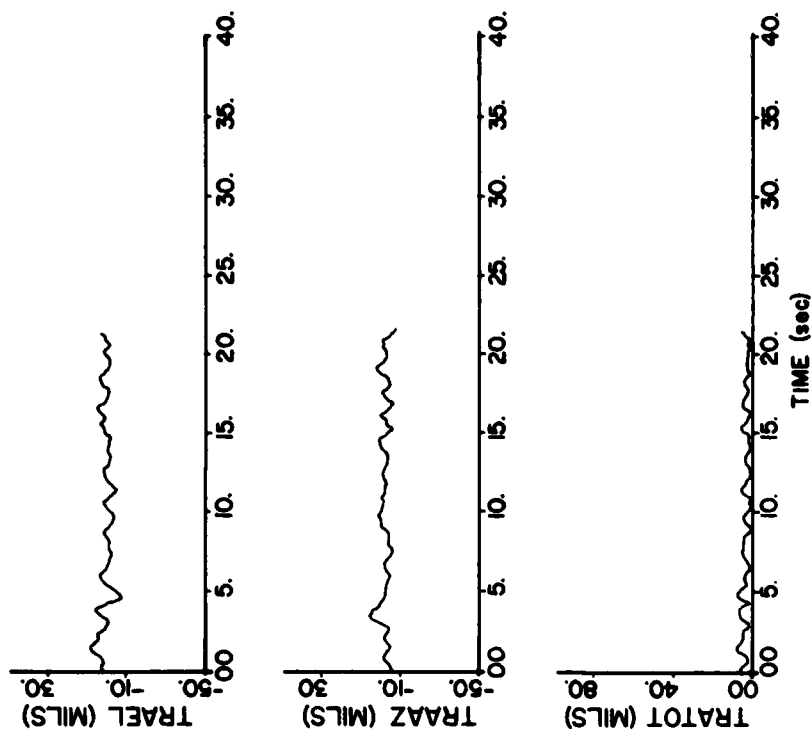
Figure 38. $K_\beta = 1.9$, $K_p = 5$, 3.7 g, Mach .7, 10000 Feet
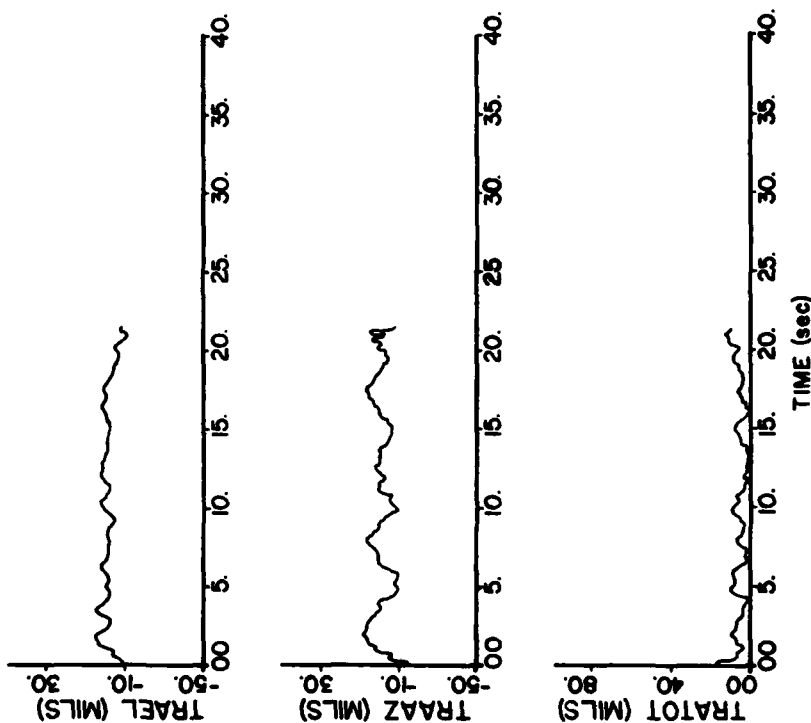
KBD=1.9. KP=2.5. 4 G, MACH .75, 10000 FEET

KBD=1.9. KP=2.5. 4, G, MACH .75, 10000 FEET
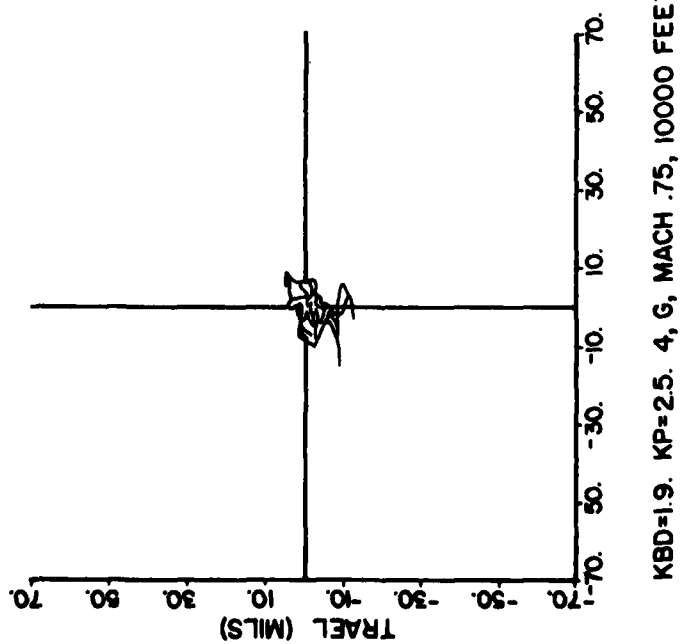
Figure 39. K_β=1.9, K_p=2.5, 4 g, Mach .75, 10000 Feet
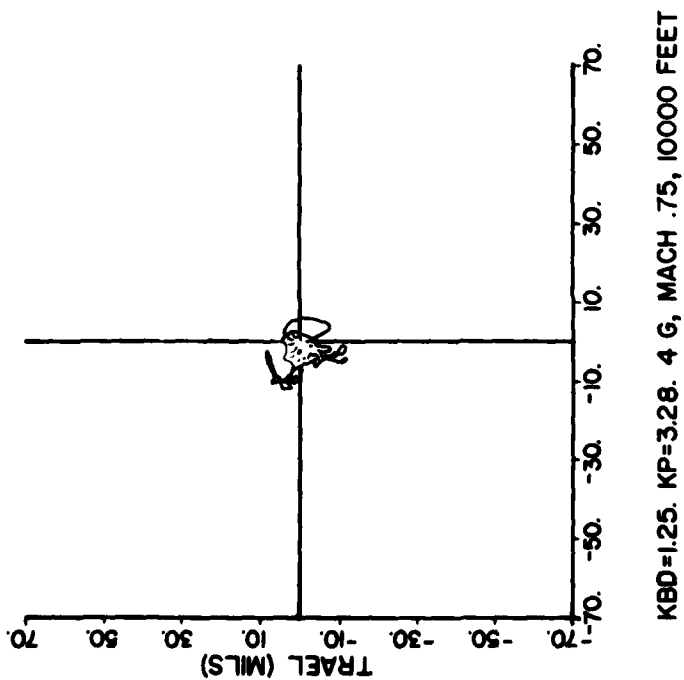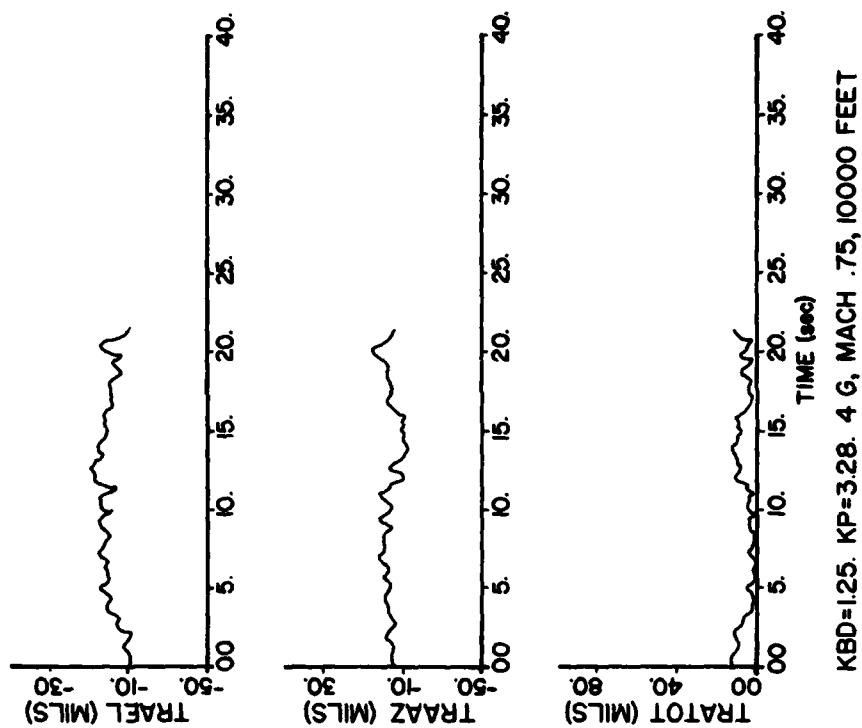
Figure 40. $K_{\dot{\beta}}$=1.25, K_p=3.28, 4 g, Mach .75, 10000 Feet

KBO=1.9. KP=2.5. 4 G, MACH .75, 10000 FEET

KBD=1.9. KP=2.5. 4 G, MACH .75, 10000 FEET

Figure 41. $K_\dot{\beta}$=1.9, K_p=2.5, 4 g, Mach .75, 10000 Feet

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KBD=1.5. KP=3.45. 4 G, MACH .75, 10000 FEET
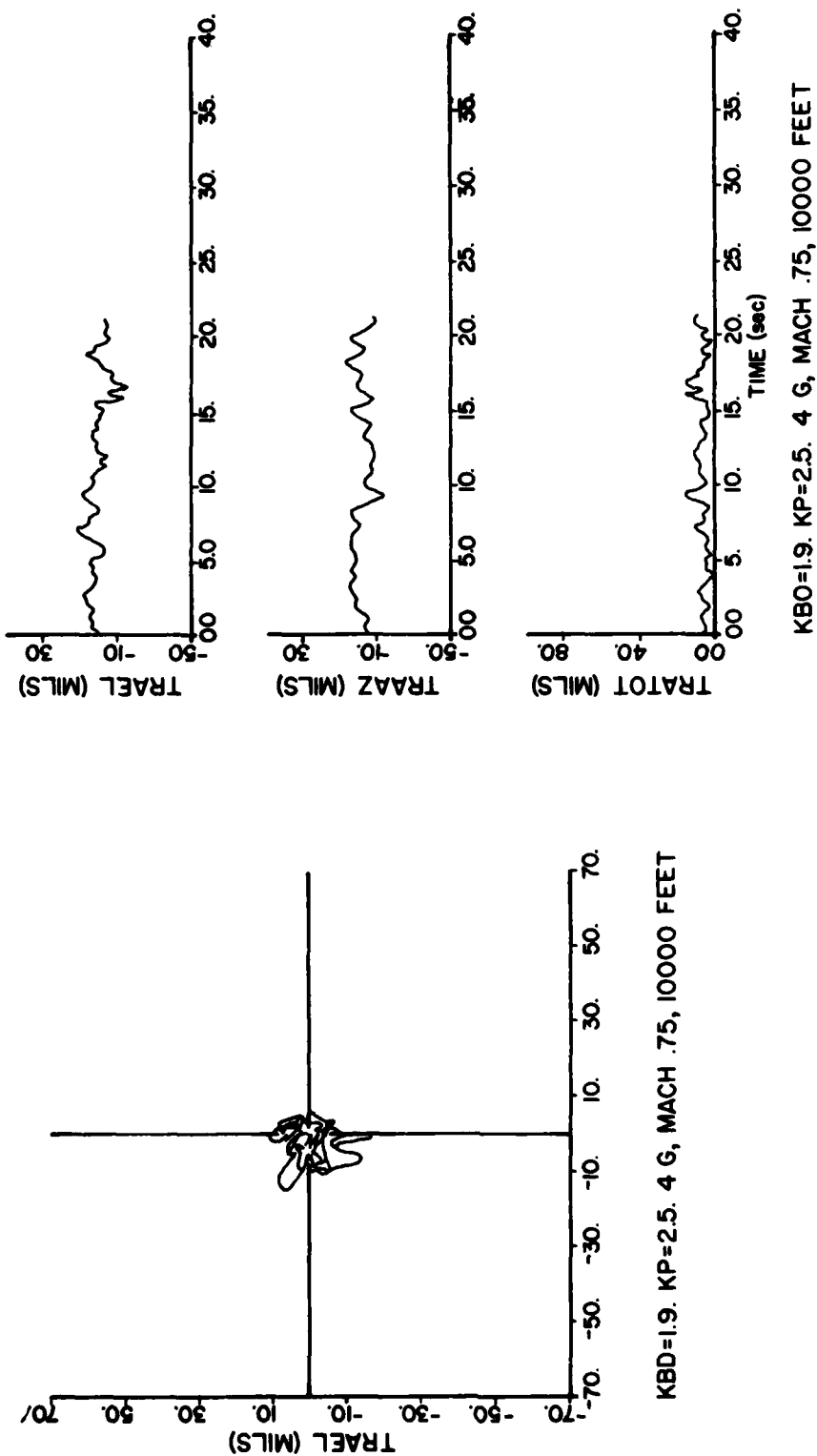
KBD=1.5. KP=3.45. 4 G, MACH .75, 10000 FEET
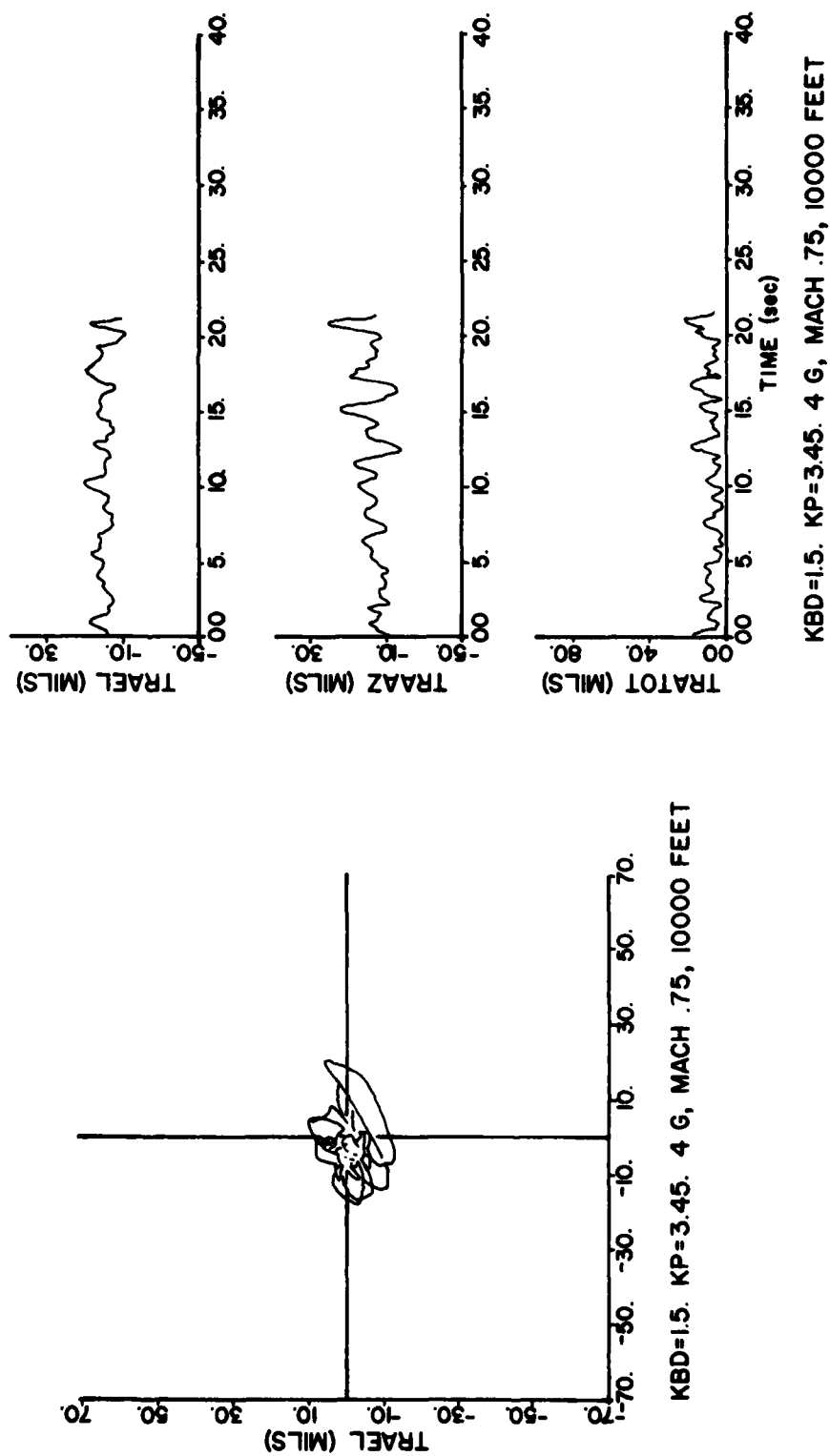
Figure 42. $K_{\dot{\beta}}$=1.5, K_p=3.45, 4 g, Mach .75, 10000 Feet
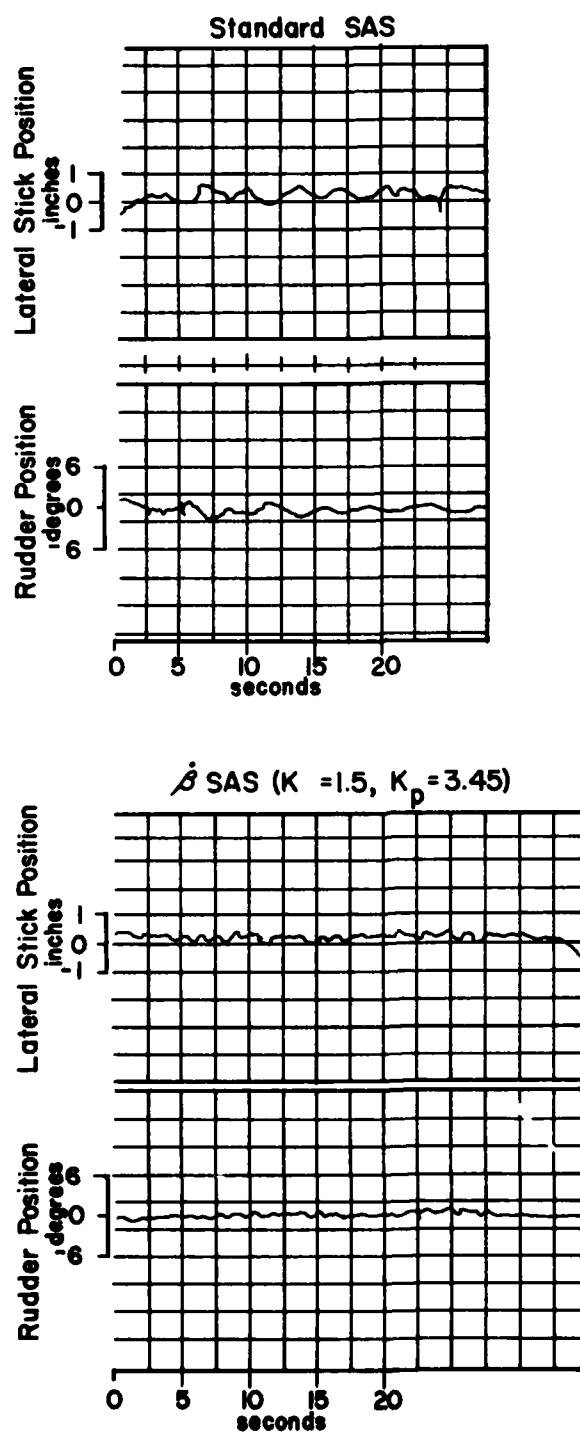
Figure 43. Pilot Workload Comparison, 4 g Tracking Task

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SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

A lateral stability augmentation system for the F-106 has been designed using sideslip rate and sideslip angle as primary feedbacks. The sideslip rate is synthesized from signals available from sensors on board the aircraft. Both time and frequency domain simulations showed that the dynamic response of the aircraft is improved using the new SAS. A piloted simulation of ATA tracking encounters was also conducted to compare the existing SAS with two configurations of the β-$\dot{\beta}$ SAS. This simulation showed that a configuration of the β-$\dot{\beta}$ SAS which allowed only $\dot{\beta}$ to be fed to the rudder demonstrated substantial improvement over the standard SAS. This improvement in standard deviation of tracking error varied from 5% to 45% depending on pilot and flight condition. Based on these piloted and non-piloted simulations, the use of a $\dot{\beta}$ feedback in place of the existing SAS on the F-106 will significantly improve lateral handling qualities during tracking.

To verify this conclusion, this system was flight tested at Tyndall AFB, Florida. The flight test results, in terms of HUD camera film data and pilot comments, confirmed this conclusion that a $\dot{\beta}$ SAS will improve the F-106 handling qualities during tracking.

2. RECOMMENDATIONS

Based on the flight test results and pilot comments, the Control Systems Development Branch of the Flight Dynamics Laboratory recommended to the Air Defense Command (ADCOM) that this modified system, using $\dot{\beta}$ as primary feedback, be retrofitted to the F-106's now in the inventory. ADCOM/DOV agreed with the conclusion that such a system would improve the F-106 flight control system; however, fiscal considerations forced a negative decision on retrofit.

APPENDIX A

ASD HYBRID SIMULATION

Part of the design process includes looking at the different SAS's in a six degree-of-freedom, nonlinear simulation. This simulation is based on force and moment equations from the GDCA report (Reference 7). The force and moment equations, composed of the aerodynamic coefficients for the F-106, are used in the simulation equations which solve for $\dot{p}$, $\dot{q}$, $\dot{r}$, $\dot{u}$, $\dot{v}$, and $\dot{w}$ (Reference 8). These simulation equations and the force and moment equations are shown below.

1. SIMULATION EQUATIONS

The following equations are the basic differential equations used in the ASD hybrid simulation.

$$\dot{p} = \frac{L}{I_x} + \dot{r}\frac{I_{xz}}{I_x} - qr\frac{(I_z - I_y)}{I_y} + pq\frac{I_{xz}}{I_x} \tag{A-1}$$

$$\dot{q} = \frac{M}{I_y} + pr\frac{(I_z - I_x)}{I_y} + (r^2 - p^2)\frac{I_{xz}}{I_y} \tag{A-2}$$

$$\dot{r} = \frac{N}{I_z} + \dot{p}\frac{I_{xz}}{I_z} - pq\frac{(I_y - I_x)}{I_x} - qr\frac{I_{xz}}{I_z} \tag{A-3}$$

$$\dot{u} = \frac{T + Fx}{m} - g\sin\theta + rv - qw \tag{A-4}$$

$$\dot{v} = \frac{Fy}{m} + g\cos\theta\sin\phi + pw - ru \tag{A-5}$$

$$\dot{w} = \frac{Fz}{m} + g\cos\theta\cos\phi + qu - pv \tag{A-6}$$

2. FORCE AND MOMENT EQUATIONS

The force and moment equations below are used as inputs to the simulation equations above. The equations include both first and second order aerodynamic effects. A more detailed description of the equations and coefficients is found in Reference 6.

$$F_x = (-C_D \cos\alpha + C_L \sin\alpha)\bar{q}S \tag{A-7}$$

$$F_y = \left\{ C_{y_\beta}\beta + C_{y_{\delta a}}\delta a + C_{y_{\delta r}}\delta r + (C_{y_p}p + C_{y_r}r)\frac{b}{2U} + [(\frac{\partial C_{y_\beta}}{\partial \alpha^2}\alpha + \right.$$
$$\left. \frac{\partial C_{y_\beta}}{\partial \alpha})\alpha + \frac{\partial C_{y_\beta}}{\partial |\beta|}|\beta|]\beta \right\}\bar{q}S \tag{A-8}$$

$$F_z = (-C_L \cos\alpha - C_D \sin\alpha + C_{z_\alpha}\alpha + C_{z_{\delta e}}\delta e)\bar{q}S \tag{A-9}$$

$$L = \left\{ (C_{1_p}p + C_{1_r}r)\frac{b}{2U} + C_{1_\beta}\beta + C_{1_{\delta a}}\delta a + C_{1_{\delta r}}\delta r + [(\frac{\partial C_{1_\beta}}{\partial \alpha |\alpha|}|\alpha| + \right.$$
$$\left. \frac{\partial C_{1_\beta}}{\partial \alpha})\alpha + \frac{\partial C_{1_\beta}}{\partial |\beta|}|\beta|]\beta + [(\frac{\partial C_{1_p}}{\partial \alpha^2}\alpha + \frac{\partial C_{1_p}}{\partial \alpha})p + \frac{\partial C_{1_r}}{\partial \alpha}r]\frac{\alpha b}{2U} \right\}\bar{q}Sb \tag{A-10}$$

$$M = [C_m + C_{m_q}\frac{\bar{c}}{2U}(q + \dot{\alpha}) + C_{m_{\delta e}}\delta e]\bar{q}S\bar{c} + (n.p. + \bar{c} - x_{c.g.})F_z \tag{A-11}$$

$$N = \left\{ C_{n_\beta}\beta + C_{n_{\delta a}}\delta a + C_{n_{\delta r}}\delta r + (C_{n_p}p + C_{n_r}r)\frac{b}{2U} + \right.$$
$$[(\frac{\partial C_{n_\beta}}{\partial \alpha^2}\alpha + \frac{\partial C_{n_\beta}}{\partial \alpha})\alpha + \frac{\partial C_{n_\beta}}{\partial |\beta|}|\beta| + \Delta C_{n_\beta}]\beta$$
$$\left. (\frac{\partial C_{n_{\delta a}}}{\partial \alpha}\alpha + \frac{\partial C_{n_{\delta a}}}{\partial \delta a}\delta e)\delta a \right\}\bar{q}Sb \tag{A-12}$$

APPENDIX B

ROOT MAP DATA FOR THE F-106

The root map technique, described in Section III.1, involves
finding numerous root loci at each flight condition. Part of the root
loci at a given flight condition are generated with fixed values of K_β
while the gain $K_{\dot\beta}$ is allowed to vary. The remaining loci have fixed
values of $K_{\dot\beta}$ while K_β varies. The transfer function used with a fixed
value for K_β is shown below. The derivation is shown in Section III.1.

$$GH)_{\text{Const } K_\beta} = \frac{K_{\dot\beta} K s (s + a)(s + K_I)}{s^3 + b's^2 + c's + d'} \tag{B-1}$$

A similar transfer function results when $K_{\dot\beta}$ is held constand and K_β
varies.

$$GH)_{\text{Const } K_{\dot\beta}} = \frac{\dfrac{K_\beta K}{1 + K_{\dot\beta} K}(s + a)(s + K_I)}{s(s^2 + b''s + c'')} \tag{B-2}$$

The tables included in this appendix contain the numerator and
denominator roots for the transfer functions used to generate the root
maps of Section III. The fixed values of $K_{\dot\beta}$ vary from 1 to 7; K_β
varies from 1 to 15.

TABLE B-1

TRANSFER FUNCTION DATA FOR MACH .4, SEA LEVEL

Constant $K_{\dot\beta}$

$K_{\dot\beta}$	$\dfrac{K}{1 + K_{\dot\beta}K}$	Numerator Roots	Denominator Roots
1	.0427	-.2, -53.23	0, $-1.64\pm i1.85$
2	.0409		0, -3.57, -1.76
3	.0393		0, -6.17, -1.05
4	.0378		0, -8.16, - .81
5	.0365		0, -9.91, - .68
6	.0352		0, -11,49,-0.6
7	.034		0, -12.96, -.54

Constant K_β

K_β	K	Numerator Roots	Denominator Roots
1	.0446	0, -.2, -53.23	$-.058$, $-.518\pm i2.82$
2			$-.090$, $-.524\pm i3.21$
3			$-.11$, $-.535\pm i3.55$
4			$-.124$, $-.551\pm i3.87$
5			$-.134$, $-.568\pm i4.16$
6			$-.142$, $-.587\pm i4.43$
7			$-.149$, $-.606\pm i4.69$
8			$-.154$, $-.626\pm i4.93$
9			$-.158$, $-.646\pm i5.17$
10			$-.161$, $-.667\pm i5.39$
11			$-.164$, $-.688\pm i5.6$
12			$-.167$, $-.709\pm i5.81$
13			$-.169$, $-.730\pm i6.00$
14			$-.171$, $-.750\pm i6.20$
15			$-.173$, $-.774\pm i6.38$

TABLE B-2

TRANSFER FUNCTION DATA FOR MACH .9, SEA LEVEL

Constant $K_{\dot{\beta}}$

$K_{\dot{\beta}}$	$\dfrac{K}{1 + K_{\dot{\beta}}K}$	Numerator Roots	Denominator Roots
1	.0641	-.2, -57.34	0, -2.77±i3.98
2	.0602		0, -4.34±i2.0
3	.0568		0, -8.99 , -2.46
4	.0538		0, -12.14, -1.78
5	.051		0, -14.72, -1.43
6	.0485		0, -16.94, -1.22
7	.0463	↓	0, -18.91, -1.07

Constant K_{β}

K_{β}	K	Numerator Roots	Denominator Roots
1	.0685	0, -.2, -57.34	-.028, -1.01 ±i5.22
2			-.049, -1.03 ±i5.57
3			-.066, -1.06 ±i5.90
4			-.079, -1.09 ±i6.22
5			-.090, -1.11 ±i6.53
6			-.099, -1.14 ±i6.82
7			-.106, -1.17 ±i7.06
8			-.113, -1.203±i7.36
9			-.119, -1.236±i7.62
10			-.123, -1.268±i7.86
11			-.128, -1.298±i8.10
12			-.132, -1.329±i8.34
13			-.136, -1.362±i8.57
14			-.139, -1.4 ±i8.79
15	↓	↓	-.142, -1.43 ±i9.0

TABLE B-3

TRANSFER FUNCTION DATA FOR MACH .7, 10000 FEET

Constant $K_\beta^\bullet$

$K_\beta^\bullet$	$\dfrac{K}{1 + K_\beta^\bullet K}$	Numerator Roots	Denominator Roots
1	.0495	$-.2,\ -78.08$	$0,\ -2.471 \pm i2.13$
2	.0472		$0,\ -6.8,\ -1.6$
3	.0451		$0,\ -10.49,\ -1.06$
4	.0431	↓	$0,\ -13.6,\ -.83$
5	.0413		$0,\ -16.37,\ -.7$
6	.0397		$0,\ -18.88,\ -.62$
7	.0382		$0,\ -21.2,\ -.56$

Constant K_β

K_β	K	Numerator Roots	Denominator Roots
1	.0521	$0,\ -.2,\ -78.077$	$-.056\ ,\ -.558 \pm i3.75$
2			$-.088\ ,\ -.566 \pm i4.26$
3			$-.1085,\ -.584 \pm i4.71$
4			$-.1229,\ -.603 \pm i5.11$
5			$-.133\ ,\ -.624 \pm i5.5$
6			$-.141\ ,\ -.645 \pm i5.85$
7	↓	↓	$-.147\ ,\ -.67 \pm i6.19$
8			$-.152\ ,\ -.69 \pm i6.51$
9			$-.156\ ,\ -.717 \pm i6.81$
10			$-.16\ ,\ -.74 \pm i7.1$
11			$-.163\ ,\ -.765 \pm i7.38$
12			$-.165\ ,\ -.79 \pm i7.64$
13			$-.168\ ,\ -.82 \pm i7.9$
14			$-.17\ ,\ -.84 \pm i8.16$
15			$-.171\ ,\ -.86 \pm i8.4$

TABLE B-4

TRANSFER FUNCTION DATA FOR MACH .6, 15000 FEET

Constant $K_{\dot\beta}$

$K_{\dot\beta}$	$\dfrac{K}{1 + K_{\dot\beta}K}$	Numerator Roots	Denominator Roots
1	.024	-.2, -102.85	0, -1.71 $\pm i2.08$
2	.0234		0, -3.82 , -1.96
3	.0229		0, -6.85 , -1.12
4	.0224		0, -9.15 , - .86
5	.022		0, -11.2 , - .72
6	.0214		0, -13.08, - .63
7	.021		0, -14.83, - .57

Constant K_{β}

$K_{\dot\beta}$	K	Numerator Roots	Denominator Roots
1	.0391	0, -.2, -68.21	-.056, -.431$\pm i3.07$
2			-.087, -.435$\pm i3.48$
3			-.107, -.446$\pm i3.84$
4			-.121, -.454$\pm i4.17$
5			-.132, -.469$\pm i4.48$
6			-.14 , -.485$\pm i4.76$
7			-.146, -.502$\pm i5.03$
8			-.151, -.519$\pm i5.29$
9			-.155, -.537$\pm i5.54$
10			-.159, -.556$\pm i5.77$
11			-.162, -.574$\pm i5.99$
12			-.165, -.593$\pm i6.21$
13			-.167, -.610$\pm i6.42$
14			-.169, -.630$\pm i6.62$
15			-.171, -.647$\pm i6.82$

TABLE B-5

TRANSFER FUNCTION DATA FOR MACH .9, 15000 FEET

$K_{\dot{\beta}}$	$\dfrac{K}{1 + K_{\dot{\beta}}K}$	Constant $K_{\dot{\beta}}$ Numerator Roots	Denominator Roots
1	.0443	-.2, -64.51	0, -2.02±i3.19
2	.0424		0, -3.31±i1.81
3	.0407		0, -6.94 , -2.04
4	.0391		0, -9.71 , -1.45
5	.0376		0, -12.01, -1.17
6	.0362		0, -14.04, -1
7	.035	↓	0, -15.91, - .88

Constant K_{β}

$K_{\dot{\beta}}$	K	Numerator Roots	Denominator Roots
1	.0463	0, -.2, -64.51	-.035, -.618±i4.11
2			-.059, -.63 ±i4.45
3			-.077, -.643±i4.77
4			-.091, -.659±i5.08
5			-.102, -.679±i5.36
6			-.11 , -.694±i5.63
7			-.12 , -.715±i5.88
8			-.13 , -.757±i6.13
9			-.13 , -.755±i6.37
10			-.13 , -.777±i6.6
11			-.14 , -.795±i6.82
12			-.14 , -.818±i7.03
13			-.15 , -.842±i7.23
14			-.15 , -.860±i7.44
15	↓	↓	-.15 , -.884±i7.63

TABLE B-6

TRANSFER FUNCTION DATA FOR MACH 1.2, 15000 FEET

Constant $K_{\dot\beta}$

$K_{\dot\beta}$	$\dfrac{K}{1 + K_{\dot\beta}K}$	Numerator Roots	Denominator Roots
1	.0376	-.2, -88.21	0, -1.91 ±14.66
2	.0363		0, -3.07 ±13.97
3	.035		0, -4.18 ±12.77
4	.0338		0, -6.79 , -3.68
5	.0327		0, -10.01, -2.49
6	.0317		0, ··12.4 , -2
7	.0307		0, -14.61, -1.69

Constant K_β

K_β	K	Numerator Roots	Denominator Roots
1	.0246	0, -.2, -102.85	-.018, -.686±15.24
2			-.033, -.688±15.48
3			-.046, -.697±15.70
4			-.057, -.702±15.92
5			-.067, -.712±16.12
6			-.075, -.717±16.33
7			-.082, -.729±16.52
8			-.089, -.739±16.72
9			-.095, -.748±16.90
10			-.100, -.755±17.08
11			-.105, -.768±17.25
12			-.109, -.775±17.42
13			-.113, -.786±17.59
14			-.117, -.797±17.75
15			-.120, -.807±17.91

TABLE B-7

TRANSFER FUNCTION DATA FOR MACH .6, 30000 FEET

Constant $K_\beta^\cdot$

$K_\beta^\cdot$	$\dfrac{K}{1 + K_\beta^\cdot K}$	Numerator Roots	Denominator Roots
1	.0221	-.2, 78.67	0, -1.18 , ±i2.01
2	.0216		0, -2.013, ±i1.272
3	.0212		0, -4.21 , -1.4
4	.0207		0, -6.14 , - .99
5	.0203		0, -7.78 , - .808
6	.0122		0, -9.82 , - .7
7	.0195		0, -10.71, - .62

Constant K_β

K_β	K	Numerator Roots	Denominator Roots
1	.0226	0, -.2, -78.67	-.051, -.31±i2.62
2			-.081, -.3 ±i2.94
3			-.1 , -.36±i3.23
4			-.12 , -.36±i3.48
5			-.13 , -.31±i3.74
6			-.135, -.32±i3.97
7			-.14 , -.33±i4.18
8			-.147, -.34±i4.39
9			-.151, -.35±i4.59
10			-.155, -.36±i4.78
11			-.157, -.37±i4.96
12			-.16 , -.38±i5.13
13			-.16 , -.39±i5.3
14			-.166, -.40±i5.47
15			-.167, -.41±i5.63

TABLE B-8

TRANSFER FUNCTION DATA FOR MACH .9, 30000 FEET

Constant $K_{\dot{\beta}}$

$K_{\dot{\beta}}$	$\dfrac{K}{1 + K_{\dot{\beta}}K}$	Numerator Roots	Denominator Roots
1	.0274	-.2, -76.56	0, -1.416±i2.551
2	.0267		0, -2.401±i1.712
3	.026		0, -4.834, -1.83
4	.0253	↓	0, -7.183, -1.257
5	.0247		0, -9.118, -1.007
6	.0241		0, -10.869, -.859

Constant K_{β}

K_{β}	K	Numerator Roots	Denominator Roots
1	.0282	0, -.2, -76.56	-.0413, -.37 ±i3.21
2			-.0686, -.37 ±i3.53
3			-.088 , -.37 ±i3.82
4			-.1 , -.38 ±i4.09
5			-.11 , -.39 ±i4.34
6			-.12 , -.40 ±i4.59
7			-.13 , -.41 ±i4.81
8			-.135 , -.42 ±i5.03
9			-.14 , -.43 ±i5.24
10			-.145 , -.44 ±i5.44
11			-.149 , -.46 ±i5.635
12			-.152 , -.47 ±i5.82
13			-.155 , -.48 ±i6.0
14	↓	↓	-.157 , -.494±i6.2
15			-.159 , -.51 ±i6.35

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TABLE B-9

TRANSFER FUNCTION DATA FOR MACH 1.4, 30000 FEET

Constant K_β^*

K_β^*	$\dfrac{K}{1 + K_\beta^* K}$	Numerator Roots	Denominator Roots
1	.0148	-.2, -81.67	0, -1.045±i4.017
2	.0146		0, -1.626±i3.817
3	.0144		0, -2.191±i3.522
4	.0142		0, -2.739±i3.113
5	.014		0, -3.272±i2.544
6	.0138		0, -3.79 ±i1.673
7	.0136		0, -5.43 -3.1593

Constant K

K_β	K	Numerator Roots	Denominator Roots
1	.015	0, -.2, -81.67	-.013 , -.448±i4.27
2			-.025 , -.45 ±i4.413
3			-.035 , -.452±i4.55
4			-.044 , -.455±i4.68
5			-.053 , -.458±i4.81
6			-.06 , -.462±i4.93
7			-.067 , -.467±i5.056
8			-.073 , -.471±i5.174
9			-.078 , -.475±i5.29
10			-.083 , -.48 ±i5.14
11			-.088 , -.49 ±i5.52
12			-.0921, -.49 ±i5.625
13			-.096 , -.50 ±i5.73
14			-.1 , -.50 ±i5.836
15			-.103 -.51 ±i5.94

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APPENDIX C

EASY DYNAMIC ANALYSIS PROGRAM

Under contract to the USAF, The Boeing Aircraft Company developed
the Environmental Systems Analysis (EASY) digital computer program.
The program was originally developed to use in designing environmental
control systems. It has since been extended to allow time and frequency
domain analysis of aircraft systems.

The program is used to describing the system to be analyzed through
the use of block diagrams and the associated interconnections. The
program supplies generic block diagrams of the airframe and engine and
the user supplies the aerodynamic data and the block diagrams
representing the control system, pilot model, gunsight algorithm or any
aircraft subsystem desired in the analysis. The F-106 was programmed
using the same set of force and moment equations as used in the ASD
Hybrid Simulation described in Appendix A.

The included listings show an example of the data required to
generate the F-106 aircraft system model with both standard and β-$\dot{\beta}$ SAS.
Also shown are the models resulting from the data and the data decks
required to produce the Bode plots at .8 Mach and 10000 feet. Figures C-1
and C-2 contain the input data and resulting models for the β-$\dot{\beta}$ and
standard SAS. Figures C-3 and C-4 contains the analysis data used to draw
the Bode plots.

```
MODEL DESCRIPTION      F136 BETADOT AND BETA SAS MODEL
ADD TABLES=CYRA,-53,CNRA,-53,CNRAA,-53,CNRADF,-53
ADD TABLES=CLZ,153,CLR,153,CLRA,113,CLRA2,153,CLRP,153,CLRA,153,
CLRF,153,CLP,153,CLRA2,153,CLP,153,CLRA,153,CNRF,153,CNR,153,
CNR,153,CNRA2,153,CNRP,153,CNRA,153,CNR2,113,CNR,153,CNR,153,CYR,153,
CYRA2,153,CYRR,153,CYRA,153,CYRR,153,CYR,153,CYR,153,CLR,153,CLRF,153,
THP,153,CLRA,153,CD3,327,CD25,727,CD5,327,CD13,327,CD15,327
ADD PARAMETERS= ,XCG,YREF,YCG,ZREF,ZCG,RPD
ADD VARIABLES=AY,AY,AZ,BETADOT
LOCATION=56      AV      INPUTS=SD
LOCATION=76      FV      INPUTS=SD(ALT=X),AV(MAC=X)
LOCATION=52      MA      INPUTS=FV(X=CT),LGTT,
LOCATION=2       FM      INPUTS=MA(Y=THP)
FOOTRON STATEMENTS
C
C        COMPUTE ACCELERATIONS IN G'S
C
      G=32.2
      AY=FU AV/G
      AV=FV AV/G
      AZ=EN AV/G
CCCCCCCC
C        COMPUTE LONGITUDINAL FORCE TERMS% FZ EN AND FX EN
CCCCCCCC
C            INTERPOLATE TO FIND LIFT COEFFICIENTS
C
      CLJ= TBLU2(MACAV,ALTSD,CLZ(3),CLZ(4),CLZ(34),1,1,-25,-5,25,5)
      CLAO= TBLU2(MACAV,ALTSD,CLA(9),CLA(4),CLA(34),1,1,-25,-5,25,5)
      CLDFO=TBLU2(MACAV,ALTSD,CLDE(9),CLDE(4),CLDE(34),1,1,-25,-5,25,5)
C
C            COMPUTE LIFT,DRAG COEFFICIENTS AND BODY AXIS FORCES
      ELEV= XE LA ERRP
      ALPHA= AL AV*RPD
      CL1= CLJ + CLAO*ALPHA + CLDFO*ELEV
C
C        LINEAR INTERPOLATION OF DRAG BETWEEN ELEVATOR SETTINGS
      DE=-X2 LA E
      IF(DE.GT.2.5) GO TO 10
      DEL=0.
      DDE=.4
      CDL=TBLU2(CL1,MACAV,CD0(16),CD0(4),CD0(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CD25(16),CD25(4),CD25(40),1,1,24,12,24,12)
      GO TO 40
10    IF(DE.GT.5.) GO TO 20
      DEL=2.5
      DDE=.4
      CDL=TBLU2(CL1,MACAV,CD25(16),CD25(4),CD25(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CD5(16),CD5(4),CD5(40),1,1,24,12,24,12)
      GO TO 40
20    IF(DE.GT.10) GO TO 30
      DEL=5.
      DDE=.2
      CDL=TBLU2(CL1,MACAV,CD5(16),CD5(4),CD5(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CD10(16),CD10(4),CD10(40),1,1,24,12,24,12)
      GO TO 40
30    DEL=10.
      DDE=.2
      CDL=TBLU2(CL1,MACAV,CD10(16),CD10(4),CD10(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CD15(16),CD15(4),CD15(40),1,1,24,12,24,12)
40    CD0=CDL + CDU*DDE*(DE - DEL)
200   CALP= COS(ALPHA)
      SALP= SIN(ALPHA)
      FZCAV= FZ CN
```

Figure C-1. EASY Model Generation Data and Resulting Model for
β-β̇ SAS

```
      FYSAV= FX EN
      FZ EN=-QS AV*(CL1*CALP + CDO*SALP) + FZ EN
      FX EN= QS AV*(CL1*SALP - CDO*CALP) + FX EN
CCCCCCCC
C           COMBINE LONGITUDINAL DYNAMICS IN "LO"
CCCCCCCC
      MM LO= TBLU2(MACAV,ALTSO,CMO(9),CMO(4),CMO(34),1,1,-25,-5,25,5)
      MO LO=2.*TBLU2(MACAV,ALTSO,CMO(9),CMO(4),CMO(34),1,1,-25,-5,25,5)
      MAOLO=MM LO
      MOELO=TBLU2(MACAV,ALTSO,CMOE(9),CMOE(4),CMOE(34),1,1,-25,-5,25,5)
CORATIONS=     LO    INPUTS=AV,LATE(X=ELE),EN
FORTRAN STATEMENTS
CCCCCCCC
C           ADJUST LONGITUDINAL MOMENTS FOR CG LOCATION
CCCCCCCC
      TNOO=TBLU2(MACAV,ALTSO,THP(9),THP(4),THP(74),1,1,-25,-5,25,5)
      TY2LO= TY2LO + (ZPEE-ZCG)*(FX2LO-FXSAV) - (THPO*C LO-XCG)*
     1             (FZ2LO-FZSAV)
CCCCCCCC
C           COMPUTE LATERAL DIRECTIONAL NONLINEAR TERMS FY1LO,TX1LO,TZ1LO
CCCCCCCC
C                INTERPOLATE TO FIND FY DERIVATIVES
C
      CYBA2O= TBLU2(MACAV,ALTSO,CYBA2(9),CYBA2(4),CYBA2(34),1,1,
     1             -25,-5,25,5)
      CYBA3O= TBLU1(MACAV,CYBA(4),CYBA(29),1,-25)
      CYBOO= TBLU2(MACAV,ALTSO,CYBO(9),CYBO(4),CYBO(34),1,1,
     1             -25,-5,25,5)
C
C                COMPUTE NONLINEAR Y FORCES
      BETA = BE AT*RBO
      FY1LO= QS AV*(BETA*(ALPHA*
     1        (CYBA2O*ALPHA + CYBAO) + CYBBO*ABS(BETA)))
C
C                INTERPOLATE TO FIND L=TY DERIVATIVES
      CLBA2O= TBLU2(MACAV,ALTSO,CLBA2(9),CLBA2(4),CLBA2(34),1,1,
     1             -25,-5,25,5)
      CLBA3O=TBLU2(MACAV,ALTSO,CLBA(9),CLBA(4),CLBA(26),1,1,-17,-5,17,5)
      CLBOO=TBLU2(MACAV,ALTSO,CLBO(9),CLBO(4),CLBO(34),1,1,-25,-5,25,5)
      CLPA2O= TBLU2(MACAV,ALTSO,CLPA2(9),CLPA2(4),CLPA2(34),1,1,
     1             -25,-5,25,5)
      CLPAO=TBLU2(MACAV,ALTSO,CLPA(9),CLPA(4),CLPA(34),1,1,-25,-5,25,5)
      CLP3O=TBLU2(MACAV,ALTSO,CLP3(9),CLP3(4),CLP3(34),1,1,-25,-5,25,5)
C
C                COMPUTE NONLINEAR L=TY TORQUES
      CNOLTY= ((CLBA2O*ABS(ALPHA) + CLBAO)*ALPHA + CLBBO*ABS(BETA))
     1        *BETA + ((CLPA2O*ALPHA + CLPAO)*P  SO + CLP3O** SO)
     2        *ALPHA*R LO*RRO2/(VT AV*VT AV)
      TX1LO=QS AV*B LO*CNOLTY
C
C                INTERPOLATE TO FIND N=TZ DERIVATIVES
      CNBA2O= TBLU2(MACAV,ALTSO,CNBA2(9),CNBA2(4),CNBA2(34),1,1,
     1             -25,-5,25,5)
      CNBAO= TBLU1(MACAV,CNBA(4),CNBA(29),1,-25)
      CNBBO=TBLU2(MACAV,ALTSO,CNBB(9),CNBB(4),CNBB(34),1,1,-25,-5,25,5)
      CNOAAO= TBLU1(MACAV,CNOAA(4),CNOAA(29),1,-25)
      CCAOEO= TBLU1(MACAV,CNBA2E(4),CNOE(29),1,-25)
C
C                COMPUTE NONLINEAR N=TZ TORQUE
      ATL = X2 LA A*RRO
      CNONLT= ALPHA*(CNBA2O*ALPHA + CNBAO) + BETA*CNBBO*ABS(BETA)
     1        + (CNOAAO*ALPHA + CCAOE2*ELEV)*ATL
      TZ1LO= QS AV*B LO*CNONLT
CCCCCCCC
C           LOOK UP LATERAL-DIRECTIONAL LINEAR COEFFICIENTS FOR LO
CCCCCCCC
```

Figure C-1. (Cont'd)

```
         YP LP=TBLU2(MACAV,ALTSO,CYP(9),CYP(4),CYP(74),1,1,-25,-5,25,5)
         YP LP=TBLU2(MACAV,ALTSO,CYP(9),CYP(4),CYP(74),1,1,-25,-5,25,5)
         YP LP=TBLU2(MACAV,ALTSO,CYP(9),CYP(4),CYP(34),1,1,-25,-5,25,5)
         YPALP=TBLU2(MACAV,ALTSO,CYPA(9),CYPA(4),CYPA(74),1,1,-25,-5,25,5)
         YCPLP=TBLU2(MACAV,ALTSO,CYPP(9),CYPP(4),CYPP(34),1,1,-25,-5,25,5)
         LP LP=TBLU2(MACAV,ALTSO,CLP(9),CLP(4),CLP(74),1,1,-25,-5,25,5)
         LP LP=TBLU2(MACAV,ALTSO,CLP(9),CLP(4),CLP(74),1,1,-25,-5,25,5)
         LP LP=TBLU2(MACAV,ALTSO,CLP(9),CLP(4),CLP(34),1,1,-25,-5,25,5)
         LPALP=TBLU2(MACAV,ALTSO,CLPA(9),CLPA(4),CLPA(34),1,1,-25,-5,25,5)
         LPPLP=TBLU2(MACAV,ALTSO,CLPP(9),CLPP(4),CLPP(34),1,1,-25,-5,25,5)
         NP LP=TBLU2(MACAV,ALTSO,CNP(9),CNP(4),CNP(34),1,1,-25,-5,25,5)
         NPALP=TBLU2(MACAV,ALTSO,CNPA(9),CNPA(4),CNPA(34),1,1,-25,-5,25,5)
         NCPLP=TBLU2(MACAV,ALTSO,CNPP(9),CNPP(4),CNPP(26),1,1,-17,-5,17,5)
         NP LP=TBLU2(MACAV,ALTSO,CNP(9),CNP(4),CNP(34),1,1,-25,-5,25,5)
         NP LP=TBLU2(MACAV,ALTSO,CNP(9),CNP(4),CNP(34),1,1,-25,-5,25,5)
LOCATION=26      LP      INPUTS=AV,LP,LA 1(X=AIL),LA R(X=RUD)
FORTRAN STATEMENTS
CCCCCCCCC
C       ADJUST LATERAL MOMENTS FOR CG POSITION
CCCCCCCCC
         TX2LP= TX2LP + (YREF-YCG)*(FZ2LP-FZSAV) - (ZREF-ZCG)*FY2LP
         TZ2LP= TZ2LP +(TNRPO*C  LP-XCG)*FY2LP -(YREF-YCG)*(FX2LP-FXSAV)
CCCCCCCCC
C       CONTROL SYSTEM MODEL
CCCCCCCCC
LOCATION=9       SP      INPUTS=LP,LP
FORTRAN STATEMENTS
         BETADOT=(P  SP*AL AV)**PP**2-P  SP*PPO + G/UO AV*
     1CCS(PITSO*RPO)*SIN(PGLSP**PPO) + EV/UO AV
         YP MC P=BETADOT
         YP MCPP=BETADOT
LOCATION=102     FUTO    INPUTS=AV(SIG=X)
LOCATION=142     FUKO    INPUTS=AV(SIG=X)
LOCATION=122     LF O    INPUTS=SP(O=X),FUTO(X=PP),FUKO(X=GAI)
LOCATION=124     SA O    INPUTS=LF O,
LOCATION=144     LA O    INPUTS=SA O,
LOCATION=164     MC E    INPUTS=LA O,,LGET(X=C4)
LOCATION=166     SA E    INPUTS=MC E,
LOCATION=164     LA E    INPUTS=SA E,
LOCATION=223     FU A    INPUTS=AV(OC=X)
LOCATION=203     MA A    INPUTS=FU A(X=C1),LGAT,
LOCATION=207     LA A    INPUTS=MA A,
LOCATION=413     MC B    INPUTS=AV(PE=X)
LOCATION=415     LA B    INPUTS=MC B
LOCATION=435     MPBD    INPUTS=LA O,LGRT(X=C4)
LOCATION=437     LFBO    INPUTS=MCRO
LOCATION=439     SABO    INPUTS=LFBO
LOCATION=459     MABO    INPUTS=SABO
LOCATION=557     LA B    INPUTS=MABO
FORTRAN STATEMENTS
*
C       OUTER LOOP FEEDBACKS FOR TRIM CALCULATIONS
C
LOCATION=312,MAAT,INPUTS=SP(ROL=X)
LOCATION=312,LGAT,INPUTS=MAAT,
LOCATION=314,MAPT,INPUTS=AV  (EV=X)
LOCATION=314,LGPT,INPUTS=MAPT,
LOCATION=317,MATT,INPUTS=SP  (ALT=X)
LOCATION=337,LGET,INPUTS=MATT,
LOCATION=329,MATT,INPUTS=AV  (MAC=X)
LOCATION=349,LGYT,INPUTS=MATT,
END OF MODEL
POINT
```

Figure C-1. (Cont'd)

Figure C-1. (Cont'd)

Figure C-1. (Cont'd)

Figure C-1. (Cont'd)

Figure C-1. (Cont'd)

Figure C-1. (Concluded)

```
MODEL DESCRIPTION    F105 STANDARD SAS MODEL
ADD TABLES=CYBA,-53,CNCA,-53,CNBAA,-53,CNBADE,-53
ADD TABLES=CLZ,158,CLL,158,CLBA,158,CLBA2,158,CLBB,158,CLBA,158,
CLDR,158,CLP,158,CLPA2,158,CLR,158,CLRA,158,CMDE,158,CMO,158,CMQ,158,
CNB,151,CNBA2,158,CNBB,158,CNBA,158,CNDR,110,CNP,158,CNR,158,CYB,158,
CYBA2,158,CYBB,158,CYBA,158,CYDR,158,CYP,158,CYR,158,CLA,158,CLDE,158,
TNP,151,CLPA,158,680,327,C125,327,C05,327,C010,327,C015,327
ADD PARAMETERS= ,XCG,YREF,YCG,ZREF,ZCG,RPO
ADD VARIABLES=AX,AY,AZ
LOCATION=56      AV      INPUTS=SO
LOCATION=76      FV      INPUTS=SO(ALT=X),AV(MAC=X)
LOCATION=52      MA      INPUTS=FI(X=C1),LGTT,
LOCATION=2       EN      INPUTS=MA(X=THR)
FORTRAN STATEMENTS
C
C          COMPUTE ACCELERATIONS IN G'S
C
      G=32.2
      AX=EU AV/G
      AY=EV AV/G
      AZ=EW AV/G
CCCCCCCCC
C          COMPUTE LONGITUDINAL FORCE TERMS% FZ EN AND FX EN
CCCCCCCCC
C          INTERPOLATE TO FIND LIFT COEFFICIENTS
C
      XLZ= TBLU2(MACAV,ALTSO,CLZ(9),CLZ(4),C-Z(34),1,1,-25,-5,25,5)
      CLAO= TBLU2(MACAV,ALTSO,CLA(9),CLA(4),CLA(34),1,1,-25,-5,25,5)
      XLBEO=TBLU2(MACAV,ALTSO,CLDE(9),CLDE(4),CLDE(34),1,1,-25,-5,25,5)
C
C          COMPUTE LIFT, DRAG COEFFICIENTS AND BODY AXIS FORCES
      ELEV= X2 LA E*RPO
      ALPHA= AL AV*RPD
      CL1= CLO + CLAC*ALPHA + CLDEO*ELEV
C
C          LINEAR INTERPOLATION OF DRAG BETWEEN ELEVATOR SETTINGS
      DE=-X2 LA E
      IF(DE.GT.2.5) GO TO 10
      DEL=0.
      DDE=.4
      CDL=TBLU2(CL1,MACAV,CO0(16),CO0(4),CO0(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CO25(16),CO25(4),CO25(40),1,1,24,12,24,12)
      GO TO 40
  10  IF(DE.GT.5.) GO TO 20
      DEL=2.5
      DDE=.4
      CDL=TBLU2(CL1,MACAV,CO25(16),CO25(4),CO25(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CO5(16),CO5(4),CO5(40),1,1,24,12,24,12)
      GO TO 40
  20  IF(DE.GT.10) GO TO 30
      DEL=5.
      DDE=.2
      CDL=TBLU2(CL1,MACAV,CO5(16),CO5(4),CO5(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CO10(16),CO10(4),CO10(40),1,1,24,12,24,12)
      GO TO 40
  30  DEL=10.
      DDE=.2
      CDL=TBLU2(CL1,MACAV,CO10(16),CO10(4),CO10(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CO15(16),CO15(4),CO15(40),1,1,24,12,24,12)
  40  CDO=CDL + (CDU - CDL)*DDE*(DE - DEL)
  200 TALP= COS(ALPHA)
      SALP= SIN(ALPHA)
```

Figure C-2.   EASY Model Generation Data and Resulting Model for
             Standard SAS

```
      LSA J= FX EN
     FXSA J= FX EN
    FZ EN= QS AV*(CL1*SA.P + CJO*SALP) + FZ EN
     FX EN= QS AV*(CL1*SA.P - CJO*CALP) + FX EN
CCCCCC;GG
C          COMBINE LONGITUDINAL DYNAMICS IN "LO"
CCCCCC;GG
      10 LO= TBLU2(MACAV,ALTSO,CMO(9),CMO(4),CMO(34),1,1,-25,-5,25,5)
      10 LO=2.*TBLU2(MACAV,ALTSO,CMQ(9),CMQ(4),CMQ(34),1,1,-25,-5,25,5)
      1ADLO=10 LO
      +DELO=TBLU2(MACAV,ALTSO,CMDE(9),CMDE(4),CMDE(34),1,1,-25,-5,25,5)
LOCATION=4        LO      INPUTS=AV,LA E(X=ELE),EN
FORTRAN STATEMENTS
CCCCCC;CC
C          ADJUST LONGITUDINAL MOMENTS FOR CG LOCATION
CCCCCC;CC
      FNPO=TBLU2(MACAV,ALTSO,TNP(9),TNP(4),TNP(34),1,1,-25,-5,25,5)
      FY2LO= TY2LO + (ZREF-ZCG)*(FX2LO-FXSAV) - (TNPO*C LO-XCG)*
     1                (FZ2LO-FZSAV)
CCCCCC;CC
C          COMPUTE LATERAL DIRECTIONAL NONLINEAR TERMS FY1LO,IX1LO,IZ1LO
CCCCCC;CC
C              INTERPOLATE TO FIND FY DERIVATIVES
C
      CYBA2O= TBLU2(MACAV,ALTSO,CYBA2(9),CY312(4),CYBA2(34),1,1,
     1    -25,-5,25,5)
      CYBAO= TBLU1(MACAV,CYBA(4),CYBA(29),1,-25)
      CYBBO= TBLU2(MACAV,ALTSO,CYBB(9),CYBB(4),CYBB(34),1,1,
     1    -25,-5,25,5)
C
C              COMPUTE NONLINEAR Y FORCES
      BETA = BE AV*RPD
      FY1LO= QS AV*(BETA*(ALPHA*
     1    (CYBA2O*ALP1A + CYBAO) + CYBB*ABS(BETA)))
C
C              INTERPOLATE TO FIND L=TX DERIVATIVES
      CLBA2O= TBLU2(MACAV,ALTSO,CLBA2(9),CLB12(4),CLB12(34),1,1,
     1    -25,-5,25,5)
      CLBAO=TBLU2(MACAV,ALTSO,CLBA(9),CLBA(4),CLBA(26),1,1,-17,-5,17,5)
      CLBBO=TBLU2(MACAV,ALTSO,CLBB(9),CLBB(4),CLBB(34),1,1,-25,-5,25,5)
      CLPA2O= TBLU2(MACAV,ALTSO,CLPA2(9),CLP12(4),CLPA2(34),1,1,
     1    -25,-5,25,5)
      CLPAO=TBLU2(MACAV,ALTSO,CLPA(9),CLPA(4),CLP1(34),1,1,-25,-5,25,5)
      CLRAO=TBLU2(MACAV,ALTSO,CLRA(9),CLRA(4),CLRA(34),1,1,-25,-5,25,5)
C
C              COMPUTE NONLINEAR L=TX TORQUES
      CNOLIN= ((CLBA2O*ABS(ALPHA) + CLBAO)*ALPHA + CLBB*ABS(BETA))
     1    *BETA + ((CLPA2O*ALPHA + CLPAO)*P SO + CLRAO*R SO)
     2    *ALPH1*C /*RPD/(VT AV*VT AV)
      TX1LO=QS AV*B LO*CNOLIN
C
C              INTERPOLATE TO FIND N=TZ DERIVATIVES
      CNBA2O= TBLU2(MACAV,ALTSO,CNBA2(9),CNB12(4),CNBA2(34),1,1,
     1    -25,-5,25,5)
      CNBAO= TBLU1(MACAV,CNBA(4),CNBA(29),1,-25)
      CNBBO=TBLU2(MACAV,ALTSO,CNBB(9),CNBB(4),CNBB(34),1,1,-25,-5,25,5)
      CNDA1O= TBLU1(MACAV,CNDA1(4),CNDA1(29),1,-25)
      CNDAEO= TBLU1(MACAV,CNDAE(4),CNDAE(29),1,-25)
C
C              COMPUTE NONLINEAR N=TZ TORQUES
      L= X2 LA 1*RPD
      CNONLI= ALPHA*((CNBA2)*ALPHA + CNBAO) + BETA*CNBBO*ABS(BETA)
     1    + (CNDA1O*ALPHA + CNDAEO*ELEV)*AIL
      FZ1LO= QS AV*B LO*CNONLI
CCCCCC;CC
C          LOOK UP LATERAL-DIRECTIONAL LINEAR COEFFICIENTS FOR LO
CCCCCC;CC
```

Figure C-2.   (Cont'd)

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```
CCCCCCCCC
      (B LO=TBLU2(MACAV,ALTSO,CYJ(9),CYB(4),CYB(34),1,1,-25,-5,25,5)
      (P LO=TBLU2(MACAV,ALTSO,CYP(9),CYP(4),CYP(34),1,1,-25,-5,25,5)
      (R LO=TBLU2(MACAV,ALTSO,CYR(9),CYR(4),CYR(34),1,1,-25,-5,25,5)
      (DALO=TBLU2(MACAV,ALTSO,CYDA(9),CYDA(4),CYDA(34),1,1,-25,-5,25,5)
      (DRLO=TBLU2(MACAV,ALTSO,CYDR(9),CYDR(4),CYDR(34),1,1,-25,-5,25,5)
      .P LO=TBLU2(MACAV,ALTSO,CLP(9),CLP(4),CLP(34),1,1,-25,-5,25,5)
      .R LO=TBLU2(MACAV,ALTSO,CLR(9),CLR(4),CLR(34),1,1,-25,-5,25,5)
      .B LO=TBLU2(MACAV,ALTSO,CLB(9),CLB(4),CLB(34),1,1,-25,-5,25,5)
      .DALO=TBLU2(MACAV,ALTSO,CLDA(9),CLDA(4),CLDA(34),1,1,-25,-5,25,5)
      .DRLO=TBLU2(MACAV,ALTSO,CLDR(9),CLDR(4),CLDR(34),1,1,-25,-5,25,5)
      IB LO=TBLU2(MACAV,ALTSO,CNB(9),CNB(4),CNB(34),1,1,-25,-5,25,5)
      (DALO=TBLU2(MACAV,ALTSO,CNDA(9),CNDA(4),CNDA(9),1,1,-25,-5,25,5)
      (DRLO=TBLU2(MACAV,ALTSO,CNDR(9),CNDR(4),CNDR(26),1,1,-17,-5,17,5)
      (P LO=TBLU2(MACAV,ALTSO,CNP(9),CNP(4),CNP(34),1,1,-25,-5,25,5)
      IR LO=TBLU2(MACAV,ALTSO,CNR(9),CNR(4),CNR(34),1,1,-25,-5,25,5)
LOCATION=26       LD      INPUTS=AV,LO,LA A(X=WIL),LA R(X=RUO)
FORTRAN STATEMENTS
CCCCCCCCC
C         ADJUST LATERAL MOMENTS FOR CG POSITION
CCCCCCCCC
      TX2LO= TX2LO + (YREF-YCG)*(FZ2LO-FZSAV) - (ZREF-ZCG)*FY2LO
      TZ2LO= TZ2LO + (XREF-XCG)*FY2LO -(YREF-YCG)*(FX2LO-FXSAV)
CCCCCCCCC
C         CONTROL SYSTEM MODEL
CCCCCCCCC
LOCATION=9        SO      INPUTS=LD,LO
LOCATION=102      FUTQ    INPUTS=AV(SIG=X)
LOCATION=142      FUKQ    INPUTS=AV(SIG=X)
LOCATION=122      LE Q    INPUTS=SO(Q=X),FUTQ(X=FO),FUKQ(X=GAI)
LOCATION=124      SA Q    INPUTS=LE Q,
LOCATION=144      LA Q    INPUTS=SA Q,
LOCATION=164      MC E    INPUTS=LA Q,LGET(X=C4)
LOCATION=166      SA E    INPUTS=MC E,
LOCATION=168      LA E    INPUTS=SA E,
LOCATION=223      FU A    INPUTS=AV(QC=X)
LOCATION=203      MA A    INPUTS=FU A(X=C1),LGAT,
LOCATION=207      LA A    INPUTS=MA A,
LOCATION=233      LE R    INPUTS=SO(R=X)
LOCATION=253      FU P    INPUTS=AV(QC=X)
LOCATION=255      LE P    INPUTS=SO(P=X),FU P(X=GAI)
LOCATION=233      MC R    INPUTS=MA A,LE R,LE P,LGRT(X=C4)
LOCATION=237      LA R    INPUTS=MC R,
C
C         OUTER LOOP FEEDBACKS FOR TRIM CALCULATIONS
C
LOCATION=312,MAAT,INPUTS=SO(ROL=X)
LOCATION=332,LGAT,INPUTS=MAAT,
LOCATION=314,MART,INPUTS=AV (E/X)
LOCATION=334,LGRT,INPUTS=MART,
LOCATION=316,MAET,INPUTS=SO (ALF=X)
LOCATION=337,LGET,INPUTS=MAET,
LOCATION=329,MATT,INPUTS=AV (MAG=X)
LOCATION=340,LGTT,INPUTS=MATT,
END OF MODEL
PRINT
```

Figure C-2.   (Cont'd)

Figure C-2. (Cont'd)

Figure C-2. (Cont'd)

Figure C-2. (Cont'd)

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Figure C-2. (Cont'd)

```
.403, .453, .50., .550, .6.1, .425., .703, .725, .500, .425
.651, .475, .933, .925, .950, .975,1.000,1.025,1.059,1.075
1.10 1.125,1.160,1.175,1.203,
   .00157800,  .00169600,  .00163900,  .00167600,  .00172000
   .00173240,  .00184120,  .00113920,  .00200000,  .00205120
   .00210720,  .00213120,  .00261720,  .00250400,  .00279600
   .00320300,  .00172130,  .00370640,  .07143010,  .00174160
   .00359960,  .00331400,  .00311240,  .00301440,  .00295000
TITLE=F196 NONLINEAR 8 035 TRIM ANALYSIS
PARAMETER VALUES
B EN=34.43,2 EO=23.755,S AV=675
TCOEN=1.,GAZEN=0,GAXEN=1.,XC EN=-11.8,ZC EN=C.
VREF=6.,L2REF=.,31,YDG=4.,2C3=-.76,2PO=.2174532C
IN1AV=1.,ALSAV=).
AN FUTO=-1,AN FUKO=-1,2C LS O=0
C1 SA O=1,C2 SA O=1.E-6,C3 SA O=1,C4 SA O=1,C5 SA O=1.E-6,
GAILA O=-1,IC LA O=.27,C6 SA O=1
C1 MC E=1,C2 MC E=0,C3 MC E=0,X2 MC E=0,X3 MC E=0
C1 SA E=1,C2 SA E=1.E-6,C3 SA E=3
C4 SA E=1,C5 SA E=1.E-6,C6 SA E=-25
GAILA E=1,IC LA E=.27
PARAMETER VALUES
AN FV=-1,2N FV=1,C2 MA=0
C2 MA A=0,GAILA A=1,IC LA A=.17
GAILS P=1,20 LS P=0,03 LS P=1,20 LS P=3,PO LS P=1
C1 MC P=1,C2 MC P=-1,C3 MC P=-1,
GAILA P=1,IC LA P=.07,2N FU P=1,2N FU A=1
C1 MART=-1.,PO LGAT=0.,20 LGAT=.5,C1 MAPT=-1.,PO LGPT=0.,20 LGPT=1.
C2 MART=-1.,PO LGTT=0.,20 LGTT=.01,C1 MATT=-1.,PO LGTT=0,20 LGTT=.2
TABLE,FTAFU A=11
0,50,100,150,200,300,400,500,600,300,900
3,3,3,1.26,.6,-.2,-.7,-1.1,-1.25,-1.5,-1.6
TABLE,FTAFU P=11
0,50,100,150,200,300,400,500,600,300,900
.2,.2,.155,.185,.27,.065,.043,.16,.035,.175
TABLE,FTAFUTO=4
0,.07,.2,1
2,2,4,20
TABLE,FTAFUKO=4
0,.05,.35,1
.2,.2,.4,.2,.1
PARAMETER VALUES
MILL=-)1.754,IXXSV=15771.,IYYSO=1*9040.,IZZSO=191110.,IXZSO=8175.
XCG=-6.74,VS AV=597.
C2 MART=0.,PO MART=0.,C2 MET=30000.,C2 MATT=.6
INITIAL CONDITIONS
ALTSO=30000.,POLSO=0.,U SO=600.
INT CONTROL=Y3VSO=0.
TITLE=F196 LATERAL DYNAMICS FOR M=.6 AT 30K FT
PRINT CONTROL=3
STEADY STATE
XIC-X
NO STATES
INT CONTROL=3  SO=1.0  SO=1.9  SO=1.U  SO=1.V  SO=1.W  SO=1
PARAMETER VALUES=1,PO LGAT=.75,C1 LA=1.25,LGPT=1,20 LGTT=1
GAILA O=0,GAXEN=0,GAILA A=1,GAILS P=1,GAILA R=0,GAILA F=0,GAZEN=0
INT CONTROL=POLSO=1
INT CONTROL=POLSO=1
INT CONTROL=2WSO=1
INT CONTROL=XI LE O=1,X2 LA O=1,X2 LA E=1
PARAMETER VALUES=GAILA E=1,GAILA A=1
INT CONTROL=X2 LA A=1
PARAMETER VALUES=GAILA A=1
INT CONTROL=XI LE P=1,XI LE P=1,X2 LA R=1
PARAMETER VALUES=GAILA P=1,GAILA P=1
INT CONTROL=ALT SO=1
```

Figure C-3. EASY β-$\dot{\beta}$ SAS Analysis Data

```
PARAMETER VALUES=GAILA R=1
INT CONTROL=X2 LA B=1,XI LEBU=1,X2 LA R=1
PARAMETER VALUES=GAILA B=1,GAILEBO=1,GAILA R=1
INT CONTROL=ALTSO=1
INT CONTROL=TH EN=1
PARAMETER VALUES=GAXEN=1
PLOT OT
TITLE=JETADOT SAS BETA/DELTA RUDDER .8,10000
TF INPIT=X2 LA R,TF OUTPUT=BE AT
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
TITLE=JETADOT SAS PHI/DELTA RUDDER .8,10000
TF INPIT=X2 LA R,TF OUTPUT=ROLSO
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
TITLE=JETADOT SAS BETA/DELTA AILERON .8,10000
TF INPIT=X2 LA A,TF OUTPUT=BE AT
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
```

——————— Figure C-3. (Concluded) ———

```
.400, .450, .500, .550, .500, .650, .700, .750, .300, .325
.650, .875, .900, .925, .950, .975,1.010,1.025,1.050,1.075
1.100,1.125,1.150,1.175,1.200,
.0015.7560,.00160605,.00163960,.00167500,.00172030
.001'8240, .0018.4120, .00189720, .00290080, .00205120
.00210720, .00212500, .00251720, .00253750, .00273600
.0035.6360, .00393220, .00395540, .00389060, .00373160
.0035.9950, .00331406, .00311240, .00301440, .00295000
TITLE='106 NONLINEAR 6 DOF TRIM ANALYSIS
PARAMETER VALUES
B  LO=18.13,C  LO=25.755,S  A/=695
TROEN=1.,GAZEN=0,GAXEN=1,YC EN=-11.8,ZO EN=1.
YREF=0. ,ZREF=-.83,YCG=0.,ZCG=-.76,RPO=.01745329
IOIAV=1.,AESAV=0;
AN FUTI=-1,AN FUKQ=-1,ZO LI Q=0
C1 SA I=1,C2 SA Q=1.E-6,C3 SA Q=1,C4 SA Q=1,C5 SA Q=1.E-6,
GAILA I=-1,TC LA Q=.07,C6 SA Q=-1
C1 MC I=1,C2 MC I=0,C3 MC I=0,X2 MC E=0,X3 MC E=0
C1 SA I=1,C2 SA E=1.E-6,C3 SA E=3
C4 SA I=1,C5 SA E=1.E-6,C6 SA E=25
GAILA I=1,TC LA E=.07
PARAMETER VALUES
AN F I=-1,BN FI=1,C2 MA=0
C2 MA I=0,GAILA A=1,TC LA I=.07
C1 MC J=2,C2 MC J=.01745329,C3 MC J=0,C4 MC J=0
GAILA I=1,TC LA J=2
C1 MCJ=-2.5,C2 MCBO=-6.5,C3 MC30=0
GAILEJ=1,PD EE60=0,ZO E33=-2
C5 SABJ=-.1047,C5 SABJ=.00J01,C4 SA30=1,C3 SA80=.1047,
C2 SABJ=.00J01,C1 SA00=1
C1 MAJ=57.3,C2 MA80=0
GAILA I=1,TO LA R=.07,AN FJ A=-1
C1 MAAI=-1.,PO LGAT=0.,ZO LGAT=.5,C1 MART=-1.,PO LGRT=0.,ZO LGRT=1.
C1 MAEI=-1.,PO LGET=0.,ZO LGET=.01,C1 MATT=-1.,PO LGTT=0,ZO LGTT=.2
TABLE,'TAFU A=11
0,50,100,150,200,300,500,910,900,300,910
3,3,3,1.25,.6,-.2,-.7,-1.1,-1.25,-1.5,-1.5
TABLE,'TAFUTQ=4
0,.07,.2,1
2,2,4,20
TABLE,'TAFUKQ=4
0,.05,.30,1
-.4,-.,.-.2,-.1
PARAMETER VALUES
MAILO=310.67,IXXSO=15771,IYYSO=189040.,IZZS)=198310.,IXZSO=4073.
XCG=-6.34,JS-AV=597.
C2 MAAI=0.,C2 MART=0.,C2 MAET=10000.,C2 MATT=.2
INITIAL CONDITIONS
ALTSO=10000.,ROLSO=0.,U  SO=862.
INT CONTROL=YAWSO=0,XI EE33=0
TITLE='105 LATERAL DYNAMICS FOR M=.8 AT 10K FT
PRINT CONTROL=3
STEADY STATE
XIC=X
NO STATES
INT CONTROL=P  SO=1,Q  SO=1,R  SO=1,V  SO=1,W  SO=1
PARAMETER VALUES=ZO LGET=0,ZO LGAT=0,ZO LGRT=0,ZO LGTT=0
GAILA I=0,GAXEN=0,GAILA I=1,GAILA G=0,GAILEJ=0,GWILA R=0,GAILA E=0,
GAZEN=1
INT CONTROL=PITSO=1
INT CONTROL=ROLSO=1
INT CONTROL=YAWSO=1
INT CONTROL=XI LE Q=1,X2 LI Q=1,X2 LA E=1
PARAMETER VALUES=GAILA E=1,GAILA J=1
INT CONTROL=X2 LA A=1
PARAMETER VALUES=....
```

Figure C-4. EASY Standard SAS Analysis Data

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```
INT CONTROL=IN EN=1
PARAMETER VALUES=GAXEN=1
PLOT 04
TITLE=STANDARD SAS BETA/DELTA RUDDER .6,30000
TF INPUT=Y2 E4 O,TF OUTPUT=1E AV
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
TITLE=STANDARD SAS PHI/DELTA RUDDER .6,30000
TF INPUT=Y2 E4 O,TF OUTPUT=0L50
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
TITLE=STANDARD SAS BETA/DELTA AILERON .6,30000
TF INPUT=Y1 E4 O,TF OUTPUT=1E AV
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
```

Figure C-4. (Concluded)

APPENDIX D

DERIVATION OF SIDESLIP RATE

The β-$\dot{\beta}$ system uses as feedbacks both sideslip (β) and sideslip rate ($\dot{\beta}$). Sideslip can be measured with a vane attached to the aircraft. Sideslip rate, on the other hand, cannot be measured directly. The β signal is too noisy to differentiate, so $\dot{\beta}$ must come from some other source. The solution to this problem begins with the definition of β.

$$\beta = \arcsin v/U \qquad (D-1)$$

v and U are the side and total velocity of the aircraft in body axis coordinates differentiating with respect to time.

$$\dot{\beta} = \frac{U\dot{v} - v\dot{U}}{U^2 + v^2} \qquad (D-2)$$

The terms in D-2 are normalized using total velocity, U.

$$\dot{\beta} = \frac{\dfrac{U}{U}\dfrac{\dot{v}}{U} - \dfrac{v}{U}\dfrac{\dot{U}}{U}}{\dfrac{U^2}{U^2} + \dfrac{v^2}{U^2}} \qquad (D-3)$$

An order of magnitude analysis is performed on Equation D-3 using the assumptions below.

$$\frac{\dot{v}}{U} << 1$$

$$\frac{v}{U} << 1$$

$$\frac{\dot{U}}{U} << 1$$

Using these assumptions, $\dot{\beta}$ is reduced to D-4.

$$\dot{\beta} = \frac{\dot{v}}{U} \qquad (D-4)$$

The $\dot{v}$ term in Equation D-4 is the side acceleration as seen by an observer in the body coordinate frame. This term cannot be measured; it must be synthesized from aircraft states which can be measured by sensors onboard the aircraft.

The total rate of change of the velocity in the inertial frame must be derived in order to get $\dot{v}$ in terms of measurable variables.

$$\dot{\bar{v}}_I = \dot{\bar{v}}_b + \bar{\omega} \times \bar{v}_b \tag{D-5}$$

$$\dot{\bar{v}}_I = \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix}_i \qquad \text{the inertial acceleration vector in body axis coordinates}$$

$$\dot{\bar{v}}_b = \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix}_b \qquad \text{the acceleration vector observed in the body frame in body axis coordinates}$$

$$\bar{\omega} = \begin{bmatrix} p \\ q \\ r \end{bmatrix} \qquad \text{the body angular rate vector in body axis coordinates}$$

$$\bar{v}_b = \begin{bmatrix} u \\ v \\ w \end{bmatrix}_b \qquad \text{the body velocity vector in body axis coordinates}$$

The y-coordinate scalar equation resulting from Equation D-5 is shown below.

$$\dot{v}_I = \dot{v} - pw + ur \tag{D-6}$$

The inertial side acceleration $\dot{v}_I$ is a measurable quantity consisting of lateral accelerometer output, $A_y)_{acc}$, summed with the gravitational component in the y-direction.

$$\dot{v}_I = A_y)_{acc} + g \cos\theta\sin\phi \qquad (D-7)$$

Using Equation D-6 and Equation D-7, $\dot{v}$ is shown below.

$$\dot{v} = pw - ur + A_y)_{acc} + g \cos\theta\sin\phi \qquad (D-8)$$

Dividing by V.

$$\frac{\dot{v}}{V} = \frac{pw}{V} - \frac{ur}{V} + \frac{A_y)_{acc}}{V} + \frac{g}{V}\cos\theta\sin\phi \qquad (D-9)$$

Equation D-9 is further simplified by assuming $\frac{w}{V}$ equal to angle of attack and $\frac{u}{V}$ equal to one.

$$\frac{\dot{v}}{V} \doteq p\alpha - r + \frac{A_y)_{acc}}{V} + \frac{g}{V}\cos\theta\sin\phi \qquad (D-10)$$

Substituting, using Equation D-4,

$$\dot{\beta} \doteq p\alpha - r + \frac{A_y)_{acc}}{V} + \frac{g}{V}\cos\theta\sin\phi \qquad (D-11)$$

Equation D-11 represents a synthesis of sideslip rate based on measurable variables.

APPENDIX E

ANALYSIS OF VARIANCE OF TRACKING DATA

A three-way analysis of variance was conducted on azimuth error, elevation error, and total error. The three error sources considered were pilot, flight condition, and SAS. Since no replications were available, the error source interactions were not examined. The analysis is based on the method described by Miller and Freund.

The model used for the analysis is shown below.

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \varepsilon_{ijk}$$

α_i = Effect due to $i\underline{\text{th}}$ pilot $i = 1, 2$

β_j = Effect due to $j\underline{\text{th}}$ SAS $j = 1, 2, 3$

γ_k = Effect due to $k\underline{\text{th}}$ flight condition $k = 1, 2, 3$

ε_{ijk} = Effect due to interactions and error

$$SSTO = \sum_{ijk}\sum\sum Y^2_{ijk} - C$$

$$SS(Pilot) = \frac{(\Sigma Y_{pilot\ 1})^2 + (\Sigma Y_{pilot\ 2})^2}{N_{pilot}} - C$$

$$SS(SAS) = \frac{(\Sigma Y_{SAS1})^2 + (\Sigma Y_{SAS2})^2 + (\Sigma Y_{SAS3})^2}{N_{SAS}} - C$$

$$SS(FC) = \frac{(\Sigma Y_{FC1})^2 + (\Sigma Y_{FC2})^2 + (\Sigma Y_{FC3})^3}{N_{FL}} - C$$

$$C = \frac{(\Sigma Y)^2}{N_{total}}$$

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TABLE E-1

AZIMUTH ERROR ANOVA

Source	SS	DOF	MS	F	Level of Significance
Pilot	26.68	1	26.68	7.8	.0163
Flt Cond	188.6	2	94.3	27.6	.00003
SAS	39.66	2	19.83	5.8	.0173
Error	41.02	12	3.42		
Total	296	17			

TABLE E-2

ELEVATION ERROR ANOVA

Source	SS	DOF	MS	F	Level of Significance
Pilot	8.76	1	8.76	7.18	.0201
Flt Cond	157.6	2	78.8	64.55	.00001
SAS	10.08	2	5.01	4.1	.044
Error	14.65	12	1.22		
Total	191.09	17			

TABLE E-3

TOTAL ERROR ANOVA

Source	SS	DOF	MS	F	Level of Significance
Pilot	33.49	1	33.49	10.97	.0053
Flt Cond	317.28	2	158.6	52	.00001
SAS	38.45	2	19.23	6.3	.0135
Error	36.65	12	3.05		
Total	425.87	17			

APPENDIX F

ASSEMBLY LISTING OF FLIGHT TEST OPERATIONAL FLIGHT PROGRAM

This appendix contains an assembled listing of the IRAM computer program used to perform the SAS calculations and the built-in test. The Hughes-built IRAM (improved reliability and maintainability) computer is a fixed-point, two's compliment airborne digital computer in the F-106 fire control system.

LOCATION INSTRUCTION SEQUENCE   'SAS CHANNEL 40 C3043.01   28 JUN 1978'   CHANNEL 40, BLOCK A   PAGE 1
                                LABEL   INST   OPERANDS   C3043

```
***    STABILITY AUGMENTATION SYSTEM (SAS) C3043
***    THIS PROGRAM HAS REVISED SCALING INCORPORATED IN
***    IT AS FOLLOWS: TRIM IS INCLUDED IN THE DIFF ELEVON
***    40=(S+TRIM)/40. TRIM IS USED TO DIFFERENTIATE S+TRIM/160
***    THE DATA LINK SWITCH IS USED TO DIFFERENTIATE BETWEEN
***    TRIMING THE ELEVONS OR RUDDER... POS 1 = ELEVON TRIM,  POS 2 =
***    RUDDER TRIM FOR THIS PROGRAM
       CYCLE TIME FOR THIS PROGRAM:
          IN SSGC3   5.32 MS
          NOT SSGC3  15.0 MS

***    THE MAIN PROGRAM STARTS AT SECTOR 0400

       /ELVON
***    CALC. DIFFERENTIAL ELEVON CMD

       BLOCK A
       ORG    0000
***    CALCULATION OF DEL SUB AC
***    DELAC = (KSURS*DELPS=KSURR*ROLL RATE + .5*TRIM)*FSUBT
       /FSUBT IS A ONE SEC FADER
       /ELVON TRA  .S*KSURR       ROLL RT VARIABLE GAIN K/.25
                   /KSURR          ROLL RT/160
              STO   /KSURR          (KSURR*RR)40
              STO   D3              LSP/4.34=2.30*LSP/40
              CLA   /KSURS         LSP VARIABLE GAIN K/4
              CLA   /DELPS          LSP/4.34=2.30*LSP/40
              SUB   /AILTM          ADD (.5*TRIM)/40
              ADD   D1             (KS=2.30+DELPS=KRR*RR+.5*TRIM)/40
              STO   /ELVNK         (1/40) LIMIT CMD TO +-[
              CLA   /FSUBT          FADER FOR ELEVON CMD
              MPY   /NOR1
              CLA   D3
              ARS   D17             +-1 DEGS +-1.0 IN ACCUM
              ADD   D17             +-1 DEG = +-0.5 IN ACCUM
              STO   ASSN            +-1 DEG = 0 TO 1 IN ACCUM
              TRA   /ELVON          OUTPUT DIFFERENTIAL ELEVON CMD
                                    EXIT
***    DATA FOR ELEVON CALC.        4.2/10
       /LSPK1 DEC  .62             1/40
       /ELVNK DEC  .1R2

                                    DISPLAY/DSPL
                                    DISPLAY A RAM LOCATION
```

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LOCATION INSTRUCTION SEQUENCE LABEL INST OPERANDS

D170,171,172,173

D180,181,182,183

D190,191,170,171,172,173
D165,166,167,168
0:0166,167,168
0:0101 = INPUT MSBS
NOT INPUTING MSBS,TRY LSBS?
STORE THE MSBS OF THE
LOCATION THAT IS TO
BE DISPLAYED.

IS D5 = 0100?
TRANSFR IF NOT 0100
INPUT LSBS
AND MSBS

DISPLAY THE DUDE

```
LOCATION INSTRUCTION SEQUENCE LABEL INST OPERANDS                    C3043                   CHANNEL 40, BLOCK B  PAGE 3

                                /STRUP  BLOCK   B400
                                        ORG     00F00          * ENTER HERE FROM MA-1 ROUTINE
                                        CLA     ZERO           * INITIALIZE FADER CONSTANT
                                        STO     /CYTIM         * CYCLE TIME = 20 MS/81.92
                                        CLA     INC            * USED IN SRWHEN
                                        SWD     3,ABC&26       * LOAD CHNL 2&3 SUBROUTINES AND CONSTANTS
                                        RDB     0FA,ABC26      * LOAD SAS ADD ON (ELEVON CALC) STUFF
                                        RDB     /TRAKC         * SET UP RETICLE AS A TRACKING CROSS
                                        TSR     /MAIN
                                /CYTIM  OCT     040            * 20MS/81.92SEC

                                *************************************************
                                *                                               *
                                *              MAIN PROGRAM                      *
                                *                                               *
                                *              MAIN PROGRAM                      *
                                *                                               *
                                *************************************************

                                ***  * CHK IF GUNSIGHT(SAS) IS SELECTED *  ***
                                /MAIN   LXI     GAQ            * D185,186,187,188
                                        TSR     S&41
                                        TSR     SRDRUM
                                        RDR     O&ARC,0        * SAS NOT SELECTED, GOODBY
                                SAS SELECTED: RUN THE MAIN PROGRAM
                                        TSR     /FADER         * CALC FADER VALUE
                                        TSR     SW3&4          * CHK HUD SW3 AND SW4 SET /KSW3 AND /KSW4
                                        TSR     /RADIN         * READ IN ALL DATA INPUTS
                                        TSR     /HOMPT         * READ HOMING POINT FOR GAIN CONSTANTS
                                        TSR     /CALC          * CALCULATE RUDDER CMD
                                        TSR     /ELVON         * CALC/DIFF ELEVON CMD
                                        TSR     /RNGDS         * READ AND DISPLAY DIGITAL PNG (ON TARGET ALT )
                                        TSR     /DSPLR         * DISPLAY RAM LOCATION (FOR DEBUGGING)
                                        SNL     SRWHEN         * FILL CYCLE TIME ( CHNL 28 )
                                        TRA     /MAIN

                                *************************************************
                                *                                               *
                                *      MAKE A 'TRACKING'/TRAKC CROSS FROM A RETICLE *
                                *                                               *
                                *************************************************
                                /TRAKC  TRA     $$
                                *  GROUND BORESIGHT CAL IS BASED ON HIGHWATER LINE, HENCE
                                *  A FACTOR OF 94 MILS IS ADDED IN ELEVATION ( AZ IS ASSUMED
                                *  TO BE ZERO). THE DISPLAY CALIBRATION IS ASSUMED TO BE
                                *  NOMINAL FOR. ANY CHANGE IS DESIRED TO THE CROSS LOCATION,
                                *  SIMPLY CHANGE EITHER /HAZ, /HEL, OR /RETSZ AS DESIRED.
```

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LOCATION INSTRUCTION SEQUENCE LABEL INST   OPERANDS

```
                              CALC THE RETICLE A.D. S
***                           /HORZ = -3.31*AZ + .5      ( POS = RT )
***                           /VERT = 3.31*EL + .5       ( POS = UP )
*  .                          /RAD = 3.31*RF*SZ
*                             SEE SNAPSHOOT PROGRAM FOR TERMINOLOGY
                   CLA  /RAZ         5 MILS/1 RADIAN
                   ADC  /TRAK1       GRND R.S. CAL  AZ
                   MPY  /TRAK3       3.31/4 * (RAZ + CAL )
                   ADC  /O2          +.5
                   STO  /R17         ;HORZ3    5 MILS/1 RADIAN
                   CLA  /REL         SC MILS/1 RADIAN
                   ADD  /TRAK2       GRND R. S.  CAL   EL
                   MPY  /TRAK3       3.31/4 * (EL + CAL)
                   ADC  /O2          +.5
                   ALS  /R17         ;VERT3
                   STO  /RETSZ       10 MILS/1 RADIAN
                   CLA  /R17
                   MPY  /RAB7
***                           SET OTHER RETICLES OFF THE HUD
                   SC   /RETSZ       ZERO
                   CLA  /R57         //VERT2
                   STO  /R17         //VERT3
                   CLA  /R17         ;HORZ2
                   STO  /R564        //HORZ1
                   CLA  /TRAK4       +.15
                   STO  /TRAK4       ;RAD2
                   STO  /TRAKC       ;RAD1
                   DEC  /.0005       5 MILS/1 RADIAN
                   DEC  /.0030       10 MILS/1 RADIAN  RETICLE WIDTH
                   DEC  /8094        GRND RS/CAL  AZ
                   DEC  /3.31R2      GRND RS/CAL  EL
                   DEC  /.15         3.31/4 = SNAPSHOOT DISPLAY GAIN V/R+4
```

ONE SECOND FADER COMPUTATION

```
/FADER TRA                          D102,110,118,126
       LXI  /SS          XFER IF HUD SW IS ON
       CLA  /G7          SW OFF, FADE OUT IF NONZERO
       TXB  /F-SUBT      LEAVE = 0
       TZR  /S+6.2       DECREMENT
       SUB  /S+2
       TRA  /R-SURT
       SUB  /FADER       EXIT
       SUI  /NOB1        OCTAL NO OF B1  IN A SEC
            /S+2         TRANSFER IF PL S IN A SEC
                         CYCLES
```

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```
LOCATION  INSTRUCTION  SEQUENCE  LABEL  INST  OPERANDS

                        /FSUBT  TRA   /FADER    TRANSFR IF FR 50 CYCLES
                        /NOB1   CLA   /FSUBT
                                ADD   B1
                                STO   /SUBT
                                TRA   /FADER
                                DATA  00062     ONE SEC FADER
                                OCT             50 CYCLES (@ 20MS/CYCLE)

            *********************************************
                              CHK HUD SWITCHES 3 AND 4
                        HUDSW  SW 3 IS D120, /KSW3 USED IN /HOMPT
                        HUD SW 4 IS D141, /KSW4 USED IN /MAIN, #2 IS READ IN /FADER.)
                        (NOTE: SW #1 IS READ IN /MAIN, #2 IS READ IN /CALC
            *********************************************
            /SW3A4  TRA   SW3A4?         ASSUME SW 3 IS ON
                    LXA   SG+2,16        D104,D112,120,128
                    CLA   ZERO,2         SW 3 IS OFF
                    STO   /KSW3

                    CLA   Z16            ASSUME SW 4 IS ON
                    LXB   SG+2,4         D141,142,143,144
                    CLA   ZERO,4
                    STO   /KSW4
            /KSW3   TRA   SW3A4
            /KSW4   DATA  00             HUD SWITCH 3 ON/OFF MARKER
                    DATA                 HUD SWITCH 4 MARKER
            *********************************************
                              READ ALL DATA INPUTS
            /RADI                 (OR INSERT FAKE DATA IF REQ'D)
            /RADI   TRA   SS             READ ALL DATA INPUTS
            *********************************************
            ** SUMMARY OF PARAMETER SCALING FOLLOWS:
            **
            *PARAMETER   INPUT    INPUT               SCALING/RESOLUTION IN
                         SCALING  RESOLUTION          CALCULATIONS
            *YAW RT      364.7    .0384 DEG/SEC       160/.00012 DEG/SEC
            *ROLL RT     196.8    .0192 DEG/SEC       500/.0038 DEG/SEC
            *YAW         7200     .10519 FPS/S        160/.00012 FPS/S
            *TRIM        240      .00079 DEG          160/.00045 DEG
            *ALPHA       0        .00079 DEG          60/.00045 DEG
            ***
                    CHK SSGC, G76  CHK SSGC, IF SSGC=3 THEN USE FAKE DATA
                    ARS   C1,12          0,D107,115,123,131
                    ANA   B312
                    STO   A
                    RDT   G73            0,D104,112,150,128
```

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LOCATION INSTRUCTION SEQUENCE LABEL INST OPERANDS

```
                                      ARS    03          0,107,115,104
                                      ADD    ◄SSGCDI     SSGC3#011
                                      STC    R2T1        NOT SSGCS,READ IN FAKE DATA
                                      SUBZ   #.#2        GO INSERT FAKE DATA
                              ***     TRA    /FAKDA      READ DATA INPUTS,COS(THETA),SIN(PHI),VSUBI (FROM
                              ***                        MACH AND IMPACT TEMP.),ROLL RATE,YAW RATE,ALPHA
                              ***                        LATERAL ACCELERATION (ASUBY) , RUDDER PEDAL POS.,TRIM.
                                      SUB    B10         .5/2**7
                                      ALS    #E10        .5SIN(THETA)
                              *COMPUTE COSINE THETA
                                      MPY    STHETA
                                      STC    STHETA
                                      SUB    B16
                                      SUB    SRSQRT
                                      TSR    ◄THETA
                                      CLA    CTHETA      .5.COS(THETA)
                                      SUB    E21         .5/2**7(.5.SIN(PHI)+.5)/2**7
                                      SUB    B10
                                      ALS    SPHI        .5SIN(PHI)
                                      RAI    E22C        (.5.COS(PHI)+.5)/2**7
                                      SUB    B10         .5/2**7
                                      ALS    CPHI        .5COS(PHI)
                              *INPUT MACH AND HSUBI   *INPUT ALTITUDE THEN MACH  *SIM*300046
                              /RV    LXA    ◄91         (1-(M=.132/2.9091)/2**3 OR
                                     RDG◄   D373        (1-(M=.1100)/81910)/2**3
                              *
                                      STC
                                      CLS    ◄
                                      ANA    B1          MACH=.13/2.9091*2**3 OR M*1100/81910*2*
                                      ADD◄   /RVK17      0=.13/2=.091*2**3) OR ZERO
                                      DVP◄   /RVK5       2**2/2**2 OR .091*2**3) OR FULL SCALE
                                      STC◄   /RVK6       MACH/2**2 OR MSUBI/81910*2**3 FEET
                                      CLA    MACH1       (LAST TIME)
                                      SUB◄   B
                                      CAL    /RVK7       0.2M/2**2 OR 4005/81910*2**3 FT,
                              * NEW INPUT IS 5 PER CENT GREATER THAN LAST TIME  ***DO-NOT-USE***
                                      SUB    /RV1
                              /RV1    STR◄   /RV2
                              /RV2    STG◄   MACH1
                                      TRX    MACH1
                              *COMPUTE VSUBI/2**11
                              /VST   CLA    MACH        M/4
                                     MPY    MACH1       M**2/16
                                     ADD    B16         (2(8) YIELDS .2M**2/4   1/4
```

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```
LOCATION  INSTRUCTION  SEQUENCE  LABEL   INST   OPERANDS          C3043
```

```
(1+.2M**2)/4
(2-865.45)/414(2**7)
414/2**9
3654/2**12
2N1T/2**12
2N1T/((1+.2M**2)*2**10
49.01/2**6
VEL. OF SOUND /2**11 FT/SEC
YIELDS VSUBI/2**11

LIMIT VSUBI TO E/GT 300FPS

V(1)/2**12
GO READ IN ALPHA
READ IN ANGLE OF ATTACK
+5V = ±25 DEGREES
(.007794)ALPHA/90 + (.007794)/2
ALPHA/90
ALPHA/90 + .5
60/90/60
ALPHA/60
ROLL AND YAW RATES
ROLL, (.007794)RR/100.00 + +.007794/2
YIELDS RR/100.00
100/160
YIELDS YR/39.37
36.37/160
YAW RT/160
(.007794*YAW RT)/39.37 + .007794
LATERAL ACCELERATION, ASUBV
(.007794)AV/200 + (.007794)/2
ASUBV/200
ASUBV/200 + .5
SCALE OVER 500
ASUBV/500
READ IN TRIM (±16) DEGREES
+-2 DEGREES
(.007794)T/4 + .007794/2
TRIM/4 + .5
TRIM/4 + .( .. 2)
```

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LOCATION INSTRUCTION SEQUENCE LABEL INST OPERANDS

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TRIM INPUT/160
LATERAL STICK POSITION
TRIM/4 FOR USE IN DIFF ELEVON CALC

LOCATION	INSTRUCTION SEQUENCE	LABEL	INST	OPERANDS
	11775	/TRIM	DATA	00
	11776	/DELPS	DATA	000
	11777	/AILTM	DATA	
	11780	/FAKDA	CLA	/F1
	11785		CLA	CTHETA
	11790		SLA	SPHI
	11795		CLA	/F2
	11800		SLA	VSUBI
	11805		SLA	/F4
	11810		SLA	ROLRT
	11815		SLA	/F5
	11820		CLA	YAWRT
	11830		CLA	/F6
	11835		STO	ALPHA

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LOCATION INSTRUCTION SEQUENCE LABEL INST OPERANDS

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LOCATION INSTRUCTION SEQUENCE LABEL   INST   OPERANDS

LATERAL STICK POSITION VARIABLE GAIN CONSTS/4

ROLL RATE GAIN CONSTANTS SCALED OVER .250

CORRECTED ANGLE OF ATTACK
KSURB/4
KSURB/16
LATERAL STICK POS VAR GAIN CONST/.25
ROLL RATF GAIN CONST/8

/KS

/KRR

/CALC

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LOCATION INSTRUCTION SEQUENCE LABEL INST OPERANDS C3043 CHANNEL 40, BLOCK C PAGE 13

```
*
***    CALCULATE RUDDER COMMAND    ***
*************************************************
***  BETA DOT EQUATION  ***
*
* BDOT=P(ALPHA)/57.3 - YAW RT +(57.3*ASUBY)(KSUBA2/VSUBI +
*                                          (57.3*G*COS(THETA*SPHI)/VSUBI
***  FOR REFERENCE THE TERMS ARE DENOTED 1ST, 2ND, 3RD, 4TH BELOW
/CALC
***  SUBTRACT 2ND FROM 3RD
        CLA>    /ASUBK       (57.3*500 )/(2048*160)=.087432
        SUB     VSUBI        V/2048 (MIN VALUE 18 300/2048=.14648)
        STO
        CLA>
*                /ASUBY       (57.3*ASUBY)/(VSUBI*160)
        MPY     /M3HA        (ASUBY*SCALED OVER 500)
        SUB     /VAWRT       YAW RATE/160 (SEE /3H3A4)
        STO                  ((57.3*ASUBY/VSUBI)-YR)/160
***  ADD 1ST TERM           (ALFAC/60
        CLA>    /ALFAC       57.3/20 (ROLL RATE)
        DVP     /ROLRK
        STO     6
*       YIELDS (P*ALPHA)/(57.3*160)
        ADD
***  ADD 4TH TERM           ( 1ST + 3RD - 2ND )/160
        CLA>    /GRAYK       (57.3*G)/(2048*20)=.045045
        DVP     VSUBI        V/2048 (MIN 18 .46482)
        STO                  (57.3*G)/V (MAX 18 .307)
        CLA>
        MPY>    CTHETA       COS(PITCH)/2
*       YIELDS (57.3*G*COS(PITCH)*SIN(ROLL))/(VSUBI*60)
        AR3     01           SCALE OVER 160
        ADD     6            (1ST + 3RD - 2ND = 4TH OVER 60)/160
        DVP     B16          TOTAL RATE/30 LIMIT OVER 60
        STO
***  RUDDER CMD EQUATION     ***
*  RUDR CMD =(KSUBP*RUDDER POS + 3*TRIM - KSUBB*BETADOT)
*  THE RESULT IS MULTIPLIED*ONE SECOND FADER, /FSUBT
/RUDDR   CLA>    /KSUBB       KSUBB/4
        STO                  (KSUBB*BETA DOT )/160
        CLA>    /KSUBP       /KSUBP/16
        SUB     /RDPOS       RUDDER POSITION FEEDBACK/10
        ADD                  (KSUBP*/RDPOS = KSUBB*BETA DOT)/160
        DVP     /TRIM        3*TRIM/160
        STO     /RUDRK       TOTAL RUDDER CMD SIGNAL
        STO                  6/160 RESCALE OVER 6
```

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LOCATION INSTRUCTION SEQUENCE LABEL INST OPERANDS

			LABEL	INST	OPERANDS	
		20630		CLA	/FSUBT	FADER
		20640		DVP	/NOR1	000144
		20650		STO	D1	ONE SEC = FULL SCALE
		20670		CLA	D0	
		20680		ARS	17	+=6DEG =+=5
		20690		ADDC	R17	ADD .5 YIELDS +=6DEG = 0 TO 1.0
		20700		STO	DCAN	
		20710		TRA	/CALC	OUTPUT RUDDER CMD
		20720	/ASURK	DEC	+0A7432	
		20740	/RURRK	DEC	+037750	
		20750	/RRATK	DEC	+055005	
		20760	/GRAVK	DEC	+045045	
		20770				READ DIGITAL/RNGDS
		20790				READ DIGITAL RNG, DISPLAY ON TARGET ALT
		20850	/RNGDS	TRA	**	FIRST DETERMINE DIG RNG CORRECT FACTORS
		20860	/K1K2	CLA	CALCON	LOC 3777
		20870		ANA	AI3T0	
		20880		ALS	04	P CORR/787
		20890		MBY	/RNGK1	.786857 GIVES CORR/.000
		20900		ADDC	B0	APPROX 2 GIVES ...LSB ERROR AVE
		20910		LGRO	01	
		20920			/RNGK2	RNG CORR/512000
		20930		CLA	CALCON	
		20940		ANA	/RBTI	OSC CORR FACTOR NOMINAL=0135
		20950		ADD>	/MINK1	MIN VALUE OF K1/3
		20960			/RNGK1	/RNGK1=OSC CORR/3
		20970		ALS	01	RANGE SCALE FACTOR
		20980		ABVC	/RNGK1	
						NOW READ DIGITAL RANGE
						RANGE IN R19T1,B18=OVERFLOW
		21010		ALB>	00563	RNG/402870 FT
		21020		ADD>	/RNGK1	123.5FT
		21030		MBY	/RNGK2	.786057
		21040		SUB>	TEMP2	RANGE DELAY CONSTANT SET BY /K1K2 SUBRT
		21050		DVP	/RNGK3	RANGE/512000.136918
		21060		STO	/RANGE	70/512=.136918
		21070		CHAD	/RANGE	
		21080		TRA	A63N	TARGET ALTITUDE
		21090			/RNGD3	
			/RANGE	DATA	00 036718	RANGE/70000
			/RNGK0	DEC	017800	TARGET ALTITUDE
			/RBTT1	OCT	003777	
			/RNGK1	OCT	003111337	RANGE/70000
			/MINK1	DATA	00 177643	70/512
						DEC .786057=402.870/512.000
						MIN VALUE OF K1/2
			•	THE END		

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LOCATION	INSTRUCTION	SEQUENCE LABEL	INST	OPERANDS	C3043
1378	39 4350	21490	END	40	
1379	39 7016	21400			

520 DRUM LOCATIONS UTILIZED, 239 REMAIN AVAILABLE IN THIS CHANNEL
TAPE SUM 0174776

GLOBAL SYMBOLS DEFINED BY AND/OR REFERENCED IN THIS CHANNEL   ***CHANNEL 40***

SYMBOL   DEF/REF

GLOBAL SYMBOLS DEFINED BY AND/OR REFERENCED IN THIS CHANNEL   ***CHANNEL 40***

SYMBOL   DEF/REF

IRAM ASSEMBLY SUMMARY INFORMATION:

CHANNEL	STATUS
40	ASSEMBLED WITHOUT ERROR
1	CHANNELS ASSEMBLED

CHANNELS WITH ASSEMBLY ERRORS (IF ANY) HAVE BEEN WRITTEN TO C3043.PRINTER.DATA

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